<u>94 - 1.4</u>
(CHP Task Number)

<u>Storm Water Impacts on Creeks</u>

Variability of Secondary Estuarine Watershed Creeks

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Abstract

The variability of water quality parameters (temperature, salinity, pH, and oxygen) was monitored in two estuarine creeks of the Charleston Harbor watershed. One watershed was a well-developed urbanized community with .3 to .5 acre housing lots, shopping centers, heavily trafficked roads, and storm drains routed into the estuary. The second site was a less well-developed forested watershed in the early stages of becoming an upstage low density housing community with 1 to 2 acre lots, golf course, and stormwater catchment system. In-situ monitoring at five minute intervals was used to assemble a composite record of annual variability. Both creeks show a strong seasonal variability driven by the annual solar cycle, a warming with the onset of spring and summer and a subsequent cooling in the fall. Oxygen and pH values are highly correlated, suggesting that a large portion of the oxygen dynamics of these creeks are controlled by biological metabolic processes. On occasion, both creeks recorded extremely low oxygen and high, above saturation, oxygen levels suggesting that a single regulatory standard for oxygen levels may be out of keeping with the dynamics of natural limits.

The summary statistics for each creek revealed no major differences between the creeks. However, analysis of the high frequency data suggests that these two creeks differ in their response to periods of intense rainfall; perturbations caused by rainfall seems to have a larger impact on creeks with urbanized watersheds. The urbanized creek displays a weaker high frequency periodic signal, perhaps due to channelization and increased sheet runoff. In the creek with a forested watershed the periodicity of the tides is conserved during rainfall as the water is intercepted by the land and released into the estuary through groundwater seepage.

Storm events trigger short term oxygen depletion in estuarine creeks by causing increases in the water column respiration rate. This increased biological oxygen demand appears to be due to anthropogenic changes in land use which diverge from the generally conservative character of natural systems. Such chronic stress may alter the natural selective forces on the creek community which may effect primary production, community structure and/or biodiversity. Such stress could be reduced by designing stormwater drainage systems for new and existing developments that better trap organic carbon and other materials and more closely mimic the path of runoff in natural systems.

Introduction

Estuaries are among the most productive of habitats, but also the most harsh, for resident organisms must adapt to continual changes that accompany the mixture of limnetic and oceanic waters. Estuaries are characterized by gradients and fluctuations in salinity, water temperature, and changes in concentrations of dissolved oxygen, particulate matter, and nutrients. Behind the biology of the estuarine system are numerous driving forces-- those of physical, chemical, and geological nature. Waters of different chemical composition (e.g. varying in chemical species and ionic strength) readily mix over a tidal cycle in a situation that is complicated by factors such as estuary topography, rainfall, sediment resuspension, and high levels of biological activity. Biogeochemical processes create not only noticeable gradients of components, but patchiness as well, depending on factors such as tidal velocity, mixing, flocculation, and uptake.

The principle input of fresh water in Charleston Harbor comes from the upland watershed of the Cooper River. The watersheds of the Ashley and Wando Rivers are in the Low Country and are fed principally through rain, groundwater seepage and runoff. The interface between these watersheds and the estuarine system are the salt marshes that border the land and are dissected by dendritic estuarine creeks.

Southeastern estuarine creeks are the primary nursery grounds for the larvae of most ecologically, commercially and recreationally important fish and crustacean species. Today, there is a growing body of evidence that the process of urbanization dramatically increases the transfer rate of terrestrial materials to coastal estuaries (Boyton et al., 1992). While there is an obvious pressing need to understand how anthropomorphic changes will interact with and change ecosystems in estuaries and coastal waters, insufficient information exists on the nature and importance of couplings between coastal watershed and estuaries. Because water is the vehicle of transport, the flow of beneficial and harmful materials is tightly coupled to the dynamics of the hydrologic cycle. Estuarine life, ranging from microscopic phytoplankton to large nekton, birds, and marine mammals, is therefore inexorably linked to rainfall in the watershed of the estuarine environment (Portnoy, 1991).

Coastal forests and other natural ecosystems play a buffering role in the conservation of ecosystem nutrients and particulates (Likens et al., 1985). Anthropogenic changes in land use such as deforestation, clearing, and agriculture disrupt the natural functioning of intricate biogeochemical cycles that tend to conserve nutrients and trap particulates in upland watersheds. Disturbance of these watersheds increases the export through the estuary in proportion to the magnitude of the perturbation. So while the transfer of terrestrial materials to the sea fuels the intense biological activity found in coastal estuaries (Day et al., 1989), human caused increases in nutrient loading may enhance primary production to the point of overload, which then leads to eutrophication. Accompanied increases in sediment loading tend to block the light required for phytoplankton production while additional dissolved and particulate carbon inputs enhance rates of microbial respiration contributing to further decreases in oxygen levels (Howarth et al., 1991). When taken *in toto*, the decline of "water quality" conditions can damage the ecological integrity of a system as evidenced by decreasing fisheries production and loss of biodiversity.

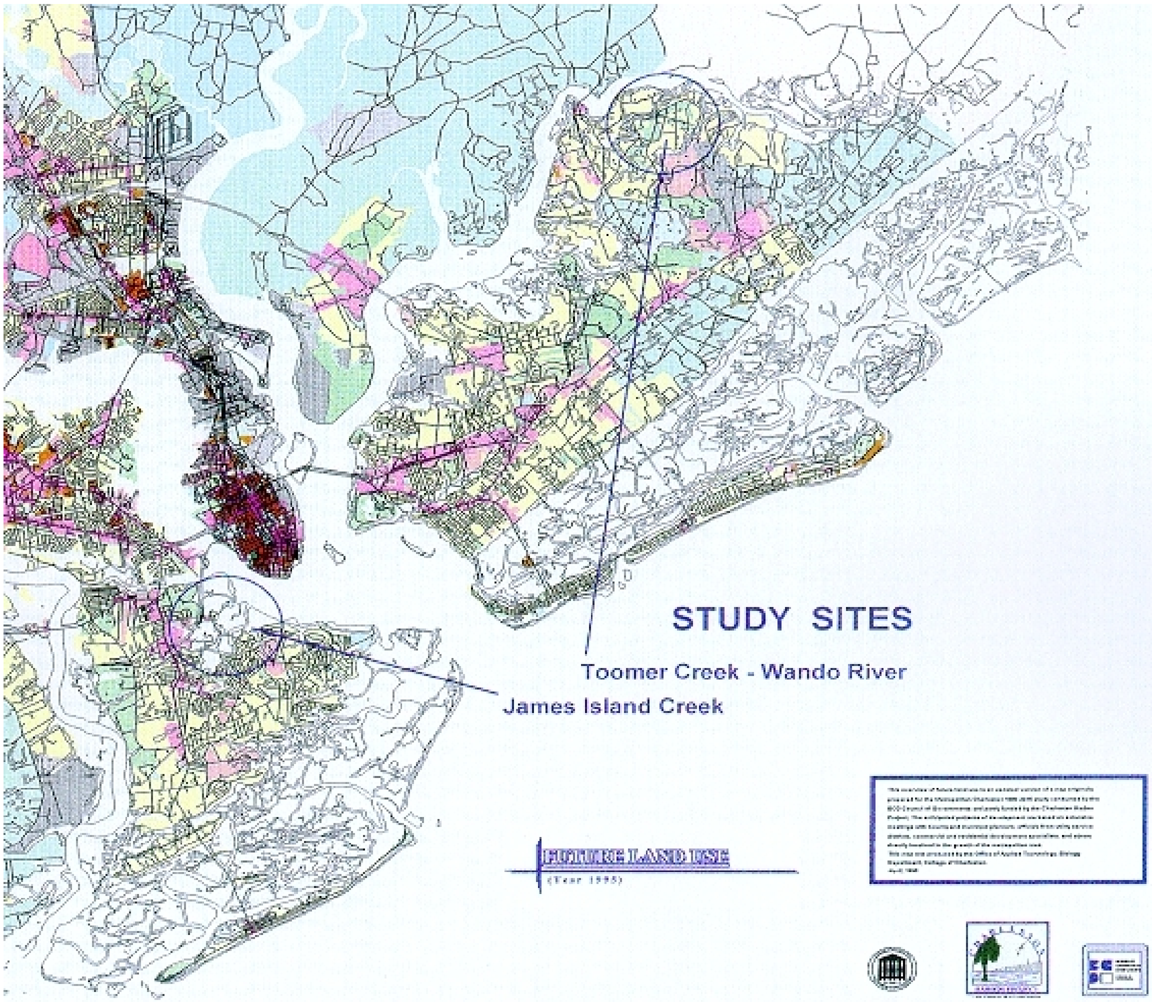
The hypothesis has its beginnings in the aftermath of Hurricane Hugo, when much of the watershed of Charleston was severely damaged. Most of the estuarine creeks became anoxic for weeks after the storm and fisheries surveys showed that larval fish year class in the estuarine creeks was virtually eliminated. Tropical Storm Klaus inundated Charleston with approximately eight inches of rain the following September which resulted again in severely depressed oxygen levels in estuarine waters.

In short, estuarine life, ranging from the microscopic plankton to fish, birds, and marine mammals inexorable linked to land use and rainfall in the watershed.

The focus of the work presented here is an attempt to characterize the natural temporal variability of water quality in two estuarine creeks, one with a watershed that is highly urbanized and the other possessing a forested watershed, to assess how watershed land use practices affect the ecology of the Charleston Harbor estuary. Hurricane Hugo, September 1989, severely damaged much of the watershed of the Charleston tri-county area. The estuarine creeks became anoxic for weeks after the storm and later surveys revealed that the year class of larval fish had been virtually eliminated. The following September, Tropical Storm Klaus inundated the region with approximately eight inches of rain which again severely depressed oxygen levels in estuarine waters (Abel et al, 1991; Dustan et al. 1991). Since these storms had dramatic effects on the ecology of estuarine creeks, I began to question the effects of long term chronic impact of land use on estuarine water quality which might possibly lead to chronic eutrophication and/or reduced habitat viability. The working hypothesis was that land use alters the coupling between coastal watershed and estuary through changes in the loading of dissolved and particulate materials. Small, but persistent increases over time might possibly change the character of estuarine creeks. Since there were virtually no data available on the high frequency variability of creeks it became necessary to sample creeks with both urbanized and forested watersheds. The forested watershed creek would be construed as the control creek so that deviations from natural patterns of variability might be detectable through time series analysis.

Study Sites

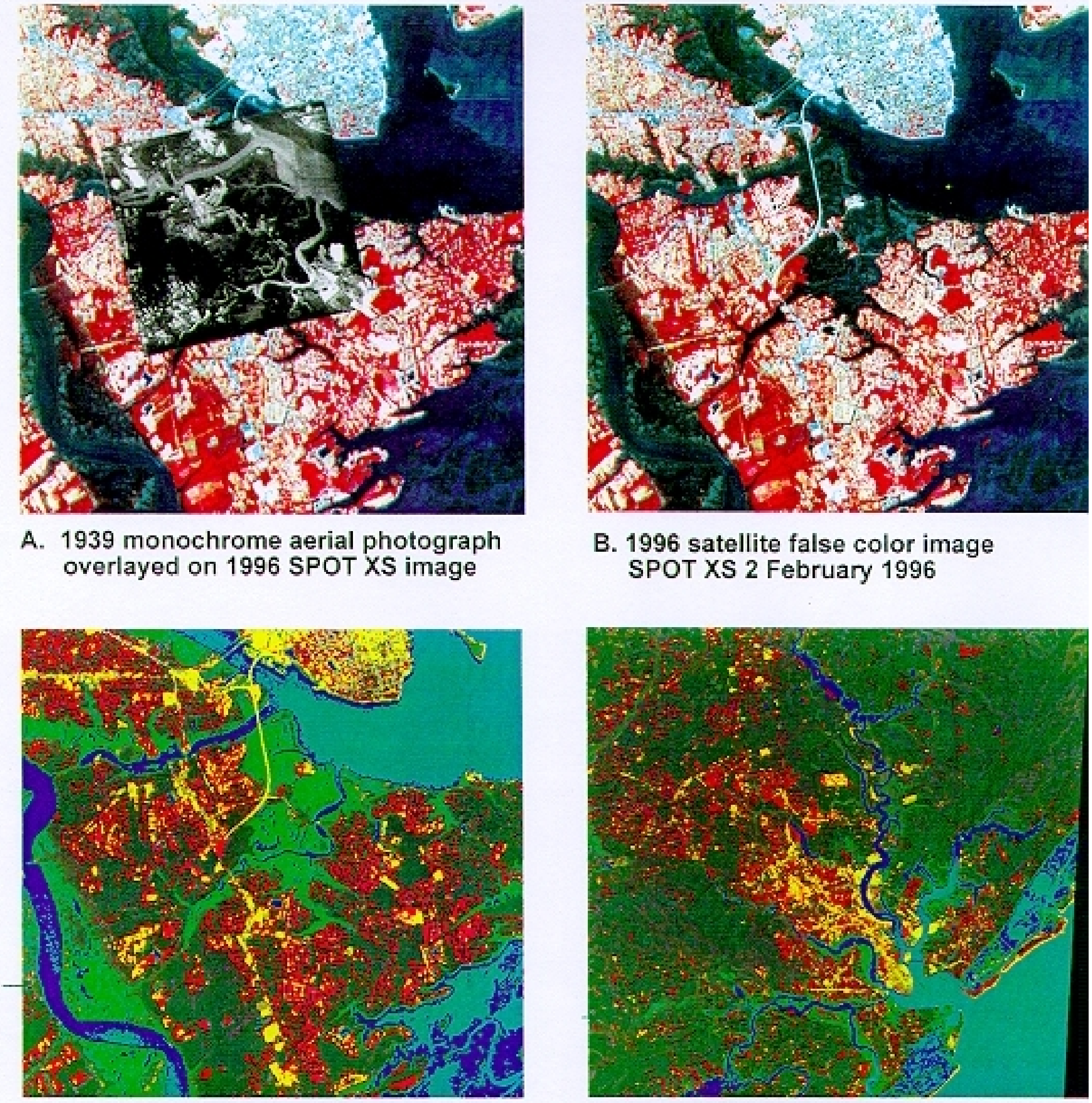
Sampling occurred in two tidal creeks in the Charleston Harbor estuary, James Island Creek and Toomer Creek (Fig. 1).



James Island Creek

James Island Creek (Fig. 2), bordered by dense salt marsh, is a small, tidally dominated tributary of Charleston Harbor, experiencing 1.6 m semidiurnal tides characteristic of the Charleston Area. Groundwater seepage is the only source of freshwater except heavy rainfall, so fresh water flow within the creek is small compared to tidal flow. The creek's watershed was farmland in 1939 (Fig. 3) with large fields on the southern side of the estuary and a cluster of smaller farms to the west of Folly Road. The golf course of the Charleston Country Club was active and there was a road leading to Plum Island. Beginning in the 1960's, the watershed slowly developed in to a medium density residential district. The mouth of James Island Creek is approximately 500 m downstream of the Plum Island wastewater treatment plant on the Ashley River. Highway runoff from Folly Road and the new James Island Expressway, which was under construction within the estuary during the sampling period, add to anthropogenic factors already influencing the creek's drainage area.

James Island Creek, Charleston, SC



A. 1939 monochrome aerial photograph overlayed on 1996 SPOT XS image

B. 1996 satellite false color image SPOT XS 2 February 1996

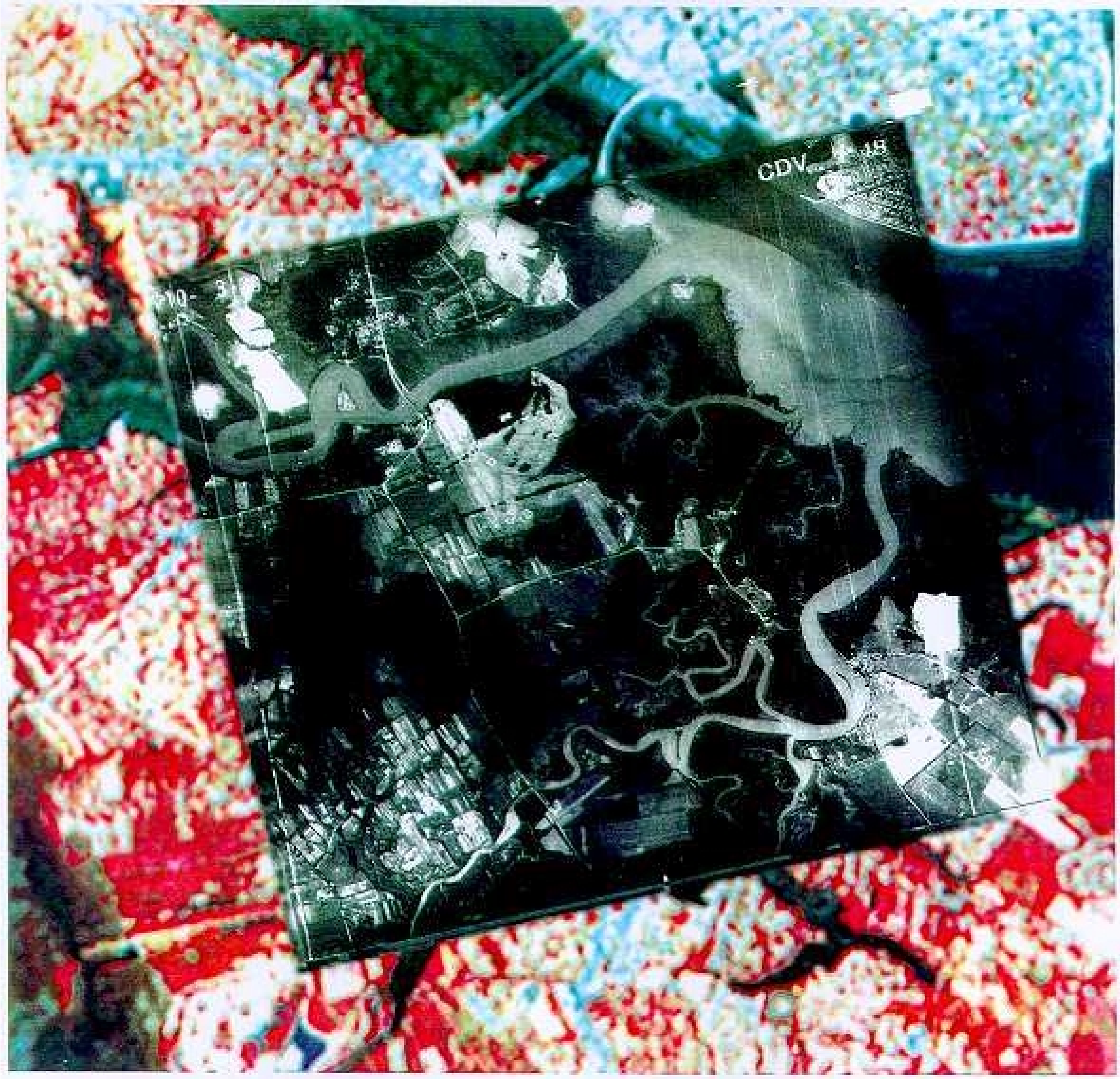
C. GIS classification of 1996 SPOT image

D. GIS classification of CHP Study Area

dense urban suburban forested

Figure 2.

James Island Creek, Charleston, SC



1939 Aerial photograph overlayed on 1996 SPOT image

Figure 3.

Toomer Creek, Dunes West

Toomer Creek (Fig.4), located in the upper reaches of the Wando River, was chosen for this project because it was one of the least disturbed forested creeks in the area that could be reached by both land and water. Additionally, it is a forested ecosystem which will be challenged ecologically in future years as its watershed becomes increasingly altered. An examination of available aerial photographs revealed that in 1989 the watershed was primarily forested and transected by only a few roads. By 1996, the property on the western shore of Toomer Creek showed signs of rapid development into an upscale residential community complete with an eighteen hole golf course. Much of the presently forested watershed of the Wando River in this region is slated to follow the path of Toomer Creek by the year 2010.

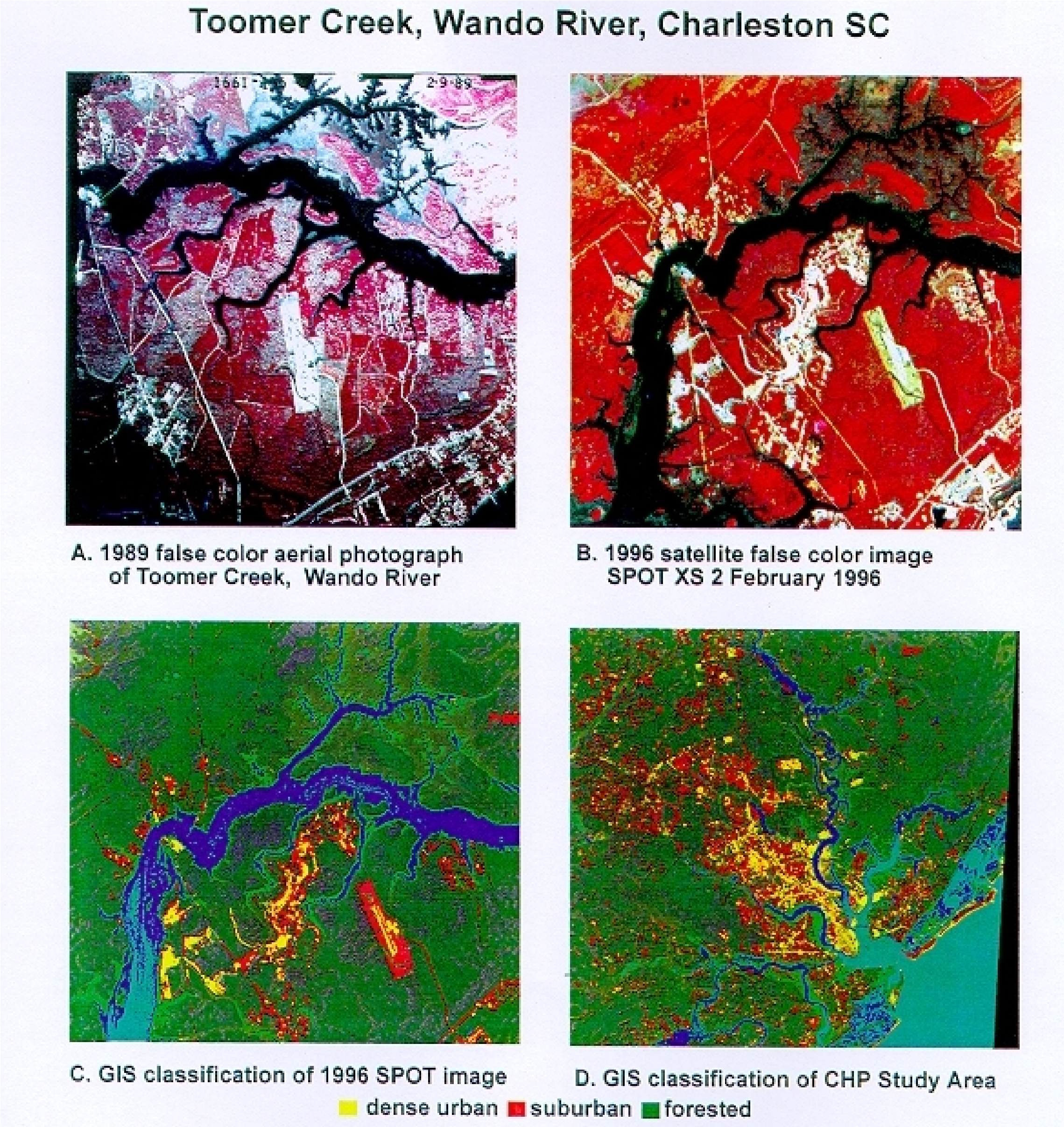


Figure 4.

Methods

Preliminary field investigations had shown that the estuarine creeks of Charleston Harbor exhibit almost no vertical stratification due to tidal mixing (Dustan et al. unpublished). For example, salinity rarely exceeds a 0.5 to 1 ppt difference between surface and bottom. As the tide floods in these creeks, friction with the sides and bottom causes tidal waves and currents which mix the water column (Pelegri , 1988, Blumberg and Goodrich, 1990, Sherwood et al., 1990, Simpson et al., 1990, Uncles and Stephens, 1990, Uncles and Stephens, l990b). Additionally, these creeks are relatively narrow, and while their maximum depths may approach 10 meters in a few areas, they are relatively shallow in relations to the fluctuation in tidal height which can be in excess of 1.8 meters. Thus, the overturn of the tides probably mixes these creeks from top-to-bottom during each tidal cycle. Bridges, boats and anything in the water can create turbulence and mix the water column (Kuo and Neilson, 1987; Schroeder et al., 1990). An additional study at James Island Creek to investigate vertical stratification during storm runoff conditions found that the water column in the creek does not become vertically stratified with respect to dissolved oxygen or salinity. Thus, under “normal” and storm conditions, a single point monitoring scheme at a strategic location could be employed to study the temporal of water quality variability within the estuarine basin.

Monitoring

Conventional sampling of water quality has been limited to irregular, widely spaced collections (monthly, etc.) which either show no trends, or are difficult to interpret. This project required continuous electronic monitoring to produce a high resolution time series data set of the natural variations which occur in this system. Sampling was carried out using self-contained, submersible, multiparameter probes (Hydrolab Datasonde™ 3) to record *in-situ* temperature, salinity, pH, and dissolved oxygen continuously at five minute intervals. The instruments were deployed from floating docks at a fixed depth of approximately 1 meter beneath the surface. They were serviced and downloaded at three to four day intervals as longer periods resulted in fouling of the oxygen membranes (Lo-Flo, HydroLab Corp.).

Instruments were deployed in both creeks during 1992-3, and again in James Island Creek during 1994 and 1995. During the summer of 1995, two and sometimes three instruments were deployed simultaneously in James Island Creek to check instrument variability. Temperature, salinity and pH calibrations were very consistent and usually within the advertised instrument error of a tenth of a unit. Readings of oxygen concentration were not as stable which necessitated careful calibration, and diligent electrode maintenance before and after every deployment,

The data were downloaded and the files concatenated into data files of a month in length. These data were summarized into weekly means to visualize annual trends. Selected time periods were used to illustrate aspects of the variability of the data and the response of each system to storms. Data analysis and statistical plotting were accomplished using Statistica™ 4.0 (Stat Soft Inc., 1994). Spectral analysis (fast fourier transformations) was performed on selected periods of continuous data (5 minute periodicity) using the algorithms in Statistica$^{TM.}$. Frequency was converted to wavelength in hours and plotted with x-y plots of spectral density vs. wavelength.

Dissolved Nutrients

Discrete samples were taken over several tidal cycles. Samples were collected in duplicate or triplicate in acid washed containers, filtered (GFF) and analyzed for dissolved plant nutrients (NO_2, NO_3, NO_4, PO_4, SiO_4). Nutrient concentrations were determined on triplicate samples using a colorimetric analysis (Hach DR2000, pillow pack and AccuVac reagent systems).

Water Column Respiration

In-vivo bottle incubations were used to estimate biological oxygen demand. Water bottles (approx. 250 ml) were taken at low tide, wrapped in aluminum foil and incubated underwater for as long as seventy two hours as preliminary studies had shown this to be more than sufficient to estimate the respiratory rate of the sample. Oxygen concentrations were determined on triplicate samples using a colorimetric analysis (Hach DR2000, AccuVac system) based on the Winkler method.

Image Analysis

Sets of images were assembled for each watershed area from available aerial photography and satellite imagery. Photographs were digitized using and Eikonix RGB digital camera system. Image processing and GIS analysis were accomplished using ERDAS^{TM} and Imagine^{TM} software.

Tides

Tidal information was obtained through Tide1: Rise & Fall^{TM} software from Micronautics, Inc.

Results

Time Series

Data records from each creek consist of a near continuous record for approximately one year. Data taken from Toomer Creek is nearly continuous from January 1993 to December 1993, excluding the months of July and August. Data from James Island Creek represents sampling from December 1992 through May 1993, and June to November 1995. The data we have collected to date are voluminous comprising time series records 88,229 long for James Island Creek and 66,961 long for Toomer Creek. These data were summarized by taking the weekly mean for each variable (Appendix 1.).

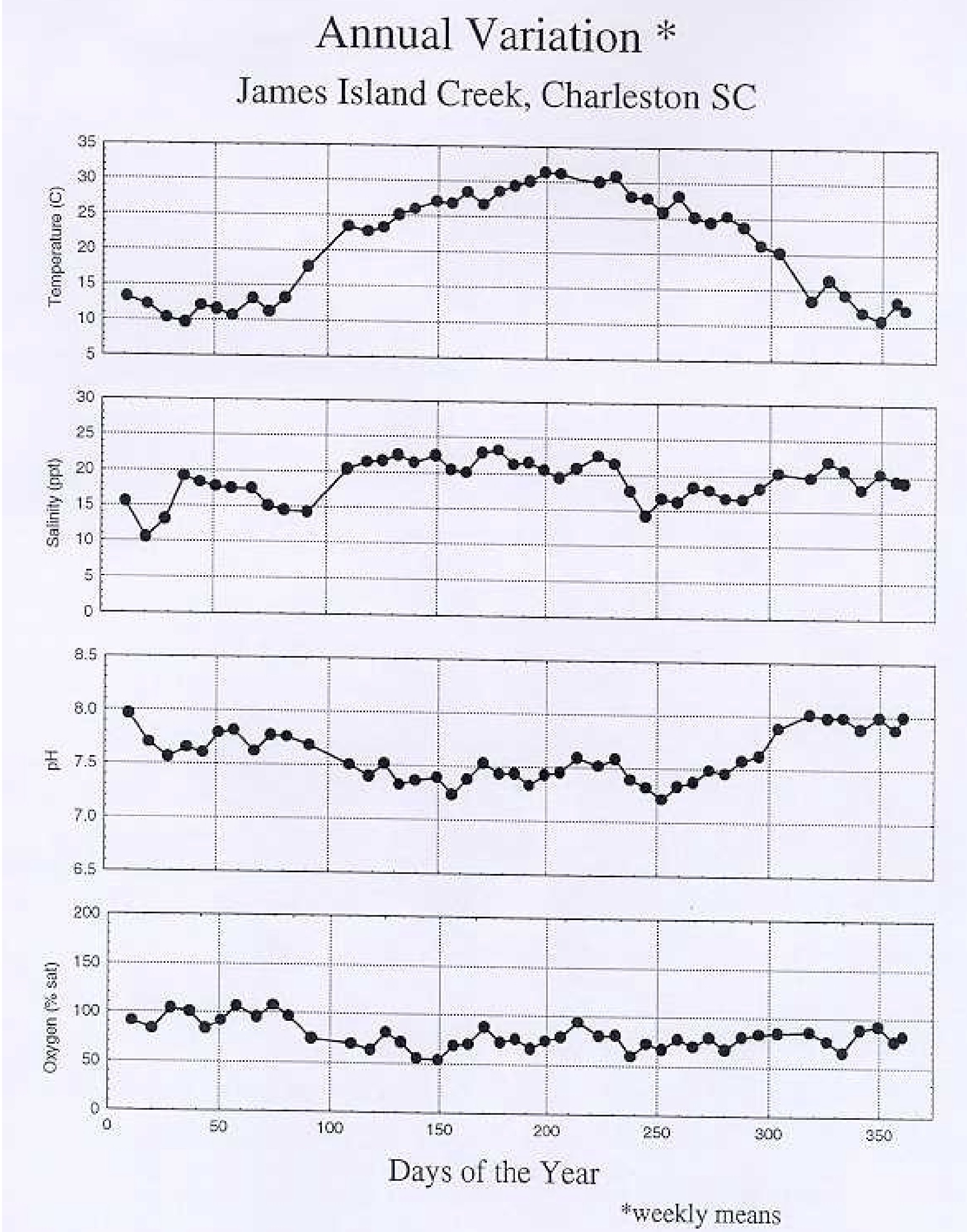

Annual Variation *
James Island Creek, Charleston SC
Temperature (C)
Salinity (ppt)
pH
Oxygen (% sat)
Days of the Year
*weekly means

Figure 5.

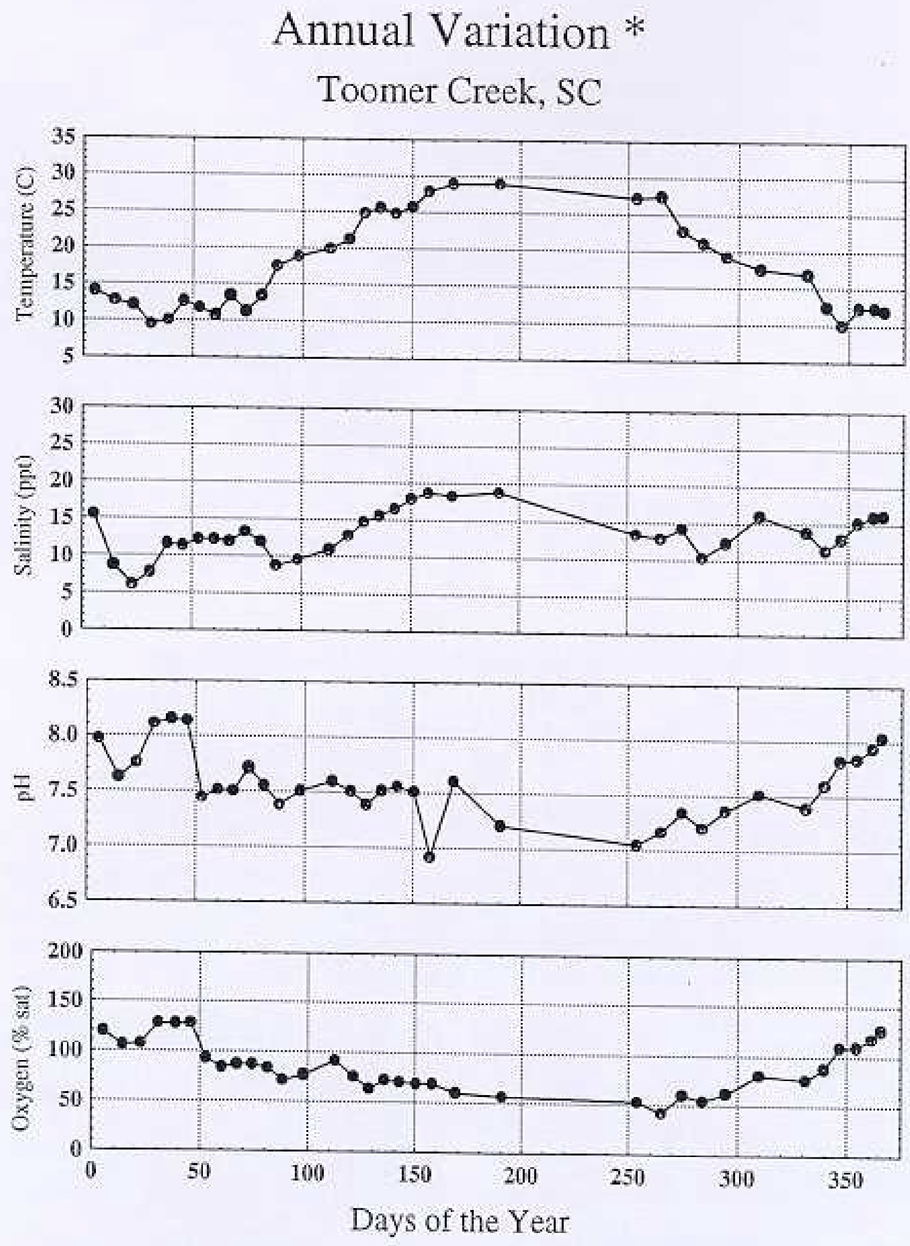


Figure 6.

Annual Variability

There are no striking differences in the descriptive statistics of the two creeks over the annual cycle (Fig. 5 and 6). Both creeks show a strong seasonal variability driven by the annual solar cycle. Both creeks show a warming with the onset of spring and summer and a subsequent cooling in the fall. Toomer Creek experienced slightly lower average temperatures (18 vs. 21.3 °C) and James Island Creek experiences a slightly warmer maximum temperature (33.6°C). Salinity tends to be highest in the spring and early summer months when rainfall is low and solar input high. Toomer Creek had a lower mean salinity (13.2 vs. 19 ppt) and a recorded zero salinity while James Island Creek dipped to 1.8 ppt (Table 1).

Table 1. Summary of water quality parameters for James Island Creek (JIC) and Toomer Creek (TC). The number of samples (n) varies due to data drop outs and missing data.

	Valid N		**Mean**		**Minimum**		**Maximum**		**Std. Dev.**	
Variable	**JIC**	**TC**	**JIC**	**TC**	**JIC**	**TC**	**JIC**	**TC**	**JIC**	**TC**
Temp. (°C)	88717	66979	21.28	18.01	7.02	4.19	33.63	31.79	7.51	6.54
pH	88718	66979	7.59	7.56	4.73	5.22	8.39	9.98	0.32	0.38
Salinity	88229	66979	18.97	13.16	1.80	0.00	27.20	20.20	3.58	3.66
Oxygen	88718	66961	79.60	84.61	4.10	0.00	200.00	194.60	21.52	25.73

Oxygen and pH in Toomer track the seasonal cycle, though not as faithfully as temperature and salinity. Recordings of pH and oxygen (percent saturation) suggest that respiration is higher in summer as temperatures increase. The mean pH of the two creeks is the same (7.6) but Toomer experienced a higher pH (9.98 vs. 8.4) and James Island Creek the lower pH (4.73 vs. 5.2). Toomer Creek experienced a higher oxygen concentration (84.6 vs. 79.6 percent saturation). On occasion, both creeks recorded extremely low oxygen and high, above saturation, oxygen levels. Toomer Creek displayed very high oxygen concentration levels in early February, while the signal was not nearly as strong in James Island Creek. Periods of extremely low oxygen levels were usually recorded in the early morning hours (pre-dawn) on low tides and seldom lasted more than a few sampling cycles (10 to 30 minutes).

The February oxygen increase in Toomer Creek is accompanied by a higher pH. This is suggestive of increased productivity. Unfortunately no data were collected to distinguish between increased benthic or phytoplankton production at the time. At James Island Creek, oxygen and pH values do not suggest a late February bloom, and in general are more variable throughout the year than at Toomer Creek. The absence of a February “bloom” in James Island Creek clearly merits further study for critical evaluation of the differences between estuarine creeks with urban and forested watersheds.

Tidal variation:

Oxygen levels strong linkage with tidal phase with oxygen levels higher at high tide. While the correlation between oxygen and salinity for each whole data set is low (0.08 and -0.17 respectively) there is a strong phase linkage between tidal stage and oxygen concentration with the highest levels of oxygen occurring on the high tide (Fig. 7). This pattern of high oxygen levels during high tide, was repeatedly observed except during periods of drought when the salinity signal was greatly dampened.

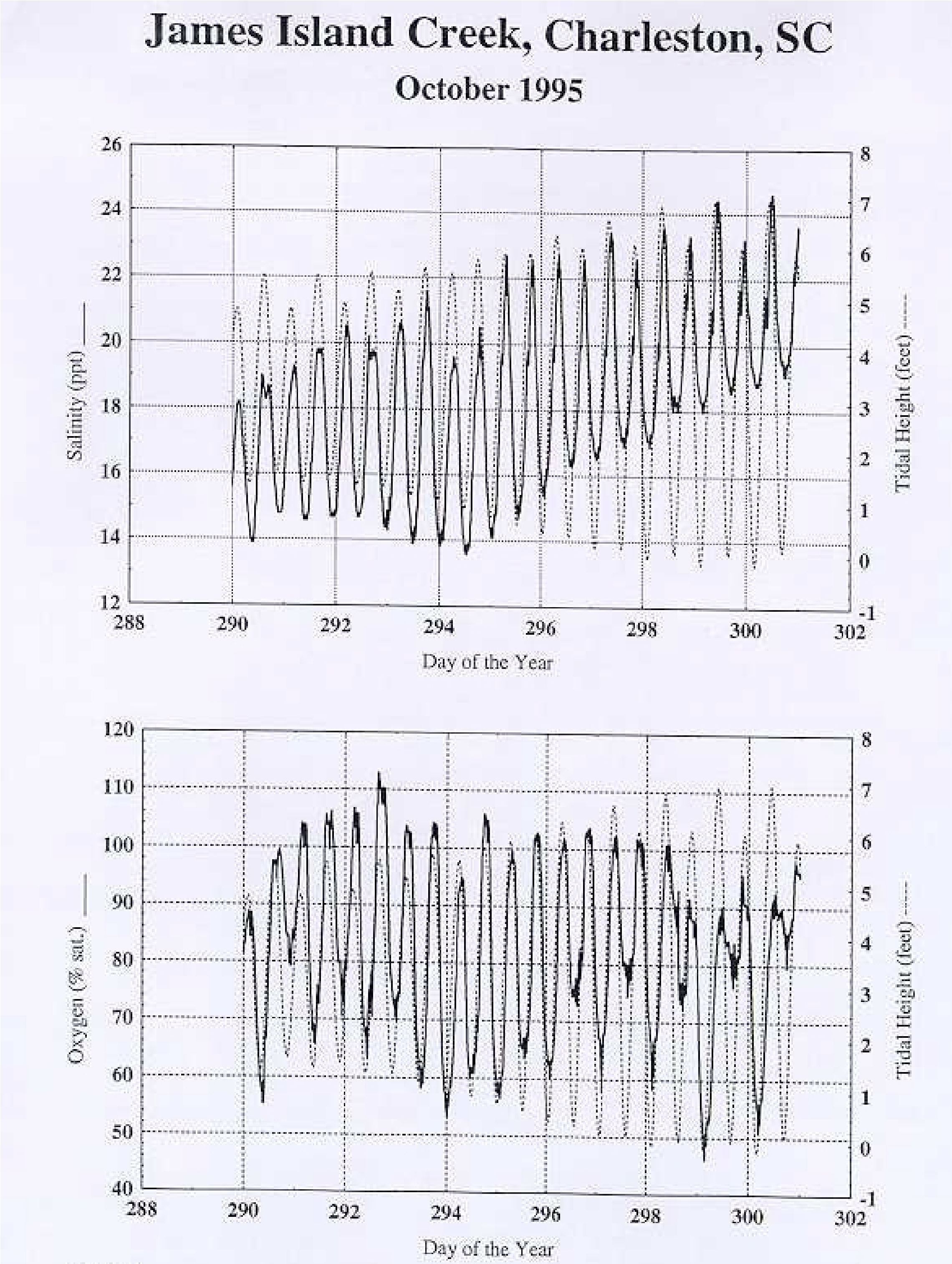


Figure 7.

Virtually all the recording show a strong positive correlation between pH and dissolved oxygen which strongly suggests that a large fraction of changes in pH are due to water column respiration (L. Burnett. per. comm.). The slope of the relationship changes seasonally and is different between creeks (Fig. 8). The pH values at the origin of each x-y plot (at zero percent oxygen) show opposite seasonal trends for the two locations. James Island Creek has lower pH value at zero oxygen in the summer months while the pH at Toomer Creek is lower at the origin in winter.

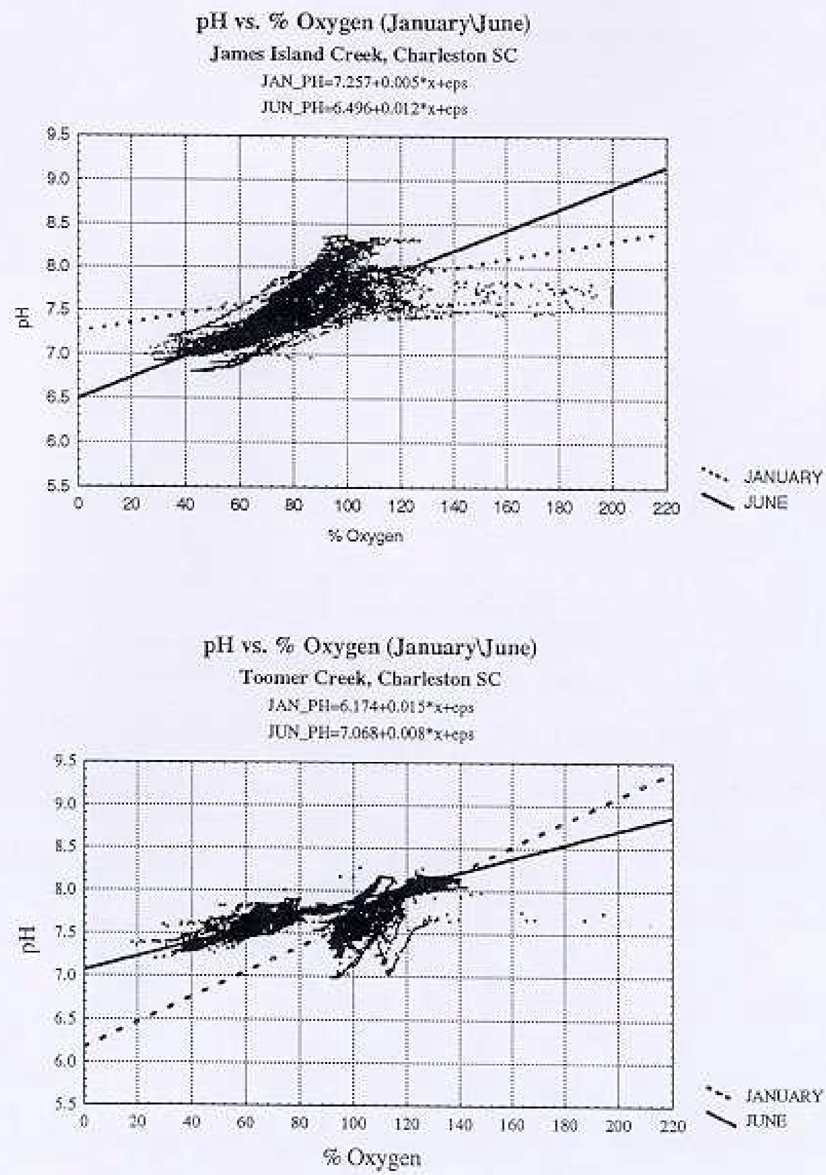


Figure 8.

Respiratory processes and dissolved organic acids (humic substances) both make significant contributions to the pH of an estuarine creek. The differences between James Island and Toomer Creeks lead one to question the relative roles of respiratory and dissolved organic acids in these two basins. Respiratory loading may be higher in James Island Creek which would explain why the lowest pH readings occur in the summer months when respiration is at its highest. Toomer Creek, more of a black water creek, exhibits lowest pH values in the winter, when rainfall leaching through the watershed may be a more active process. The watershed of James Island Creek is well tended with much of the yard waste, lawn clipping and tree leaves, being carted out of the system. The loss of natural vegetation combined with increased input from urban agricultural waste (lawn clippings, disturbed soils, etc.) and the loss of the forest root mat infrastructure to trap and/or absorb runoff, might result in higher summer respiratory rates (from the addition of substrate) and reduced addition of naturally acidic leachate (decreased input of acidic materials). On the other hand, Toomer Creek, with less developed lands, would have a greater proportion of land covered with forest leaf litter from the mixed pine and hardwood vegetation. Leaching from such detrital material is relatively rich in humic acids which might tend to lower the pH of the surrounding waters. Particulates are more likely to be trapped in the soils as the ground water percolation appears to be greater that surface runoff in forested vs urbanized systems, which might reduce the respiratory loading input into Toomer Creek.

Storm Event.

A severe winter storm in March of 1993 was simultaneously recorded in both creeks (Fig. 9 and 10). A creek to creek comparison of the records reveals that salinity dropped faster and lower in James Island Creek. The regular tidal periodicity was maintained in both creeks however, the signal in James Island Creek seemingly became more chaotic or noisy during and after the storm. The pH appeared to have more high frequency noise in James Island Creek but dropped lower in Toomer, possibly due to the influx of dissolved organic acids from decaying vegetation. Oxygen levels dropped at both sites with a greater loss at James Island Creek.

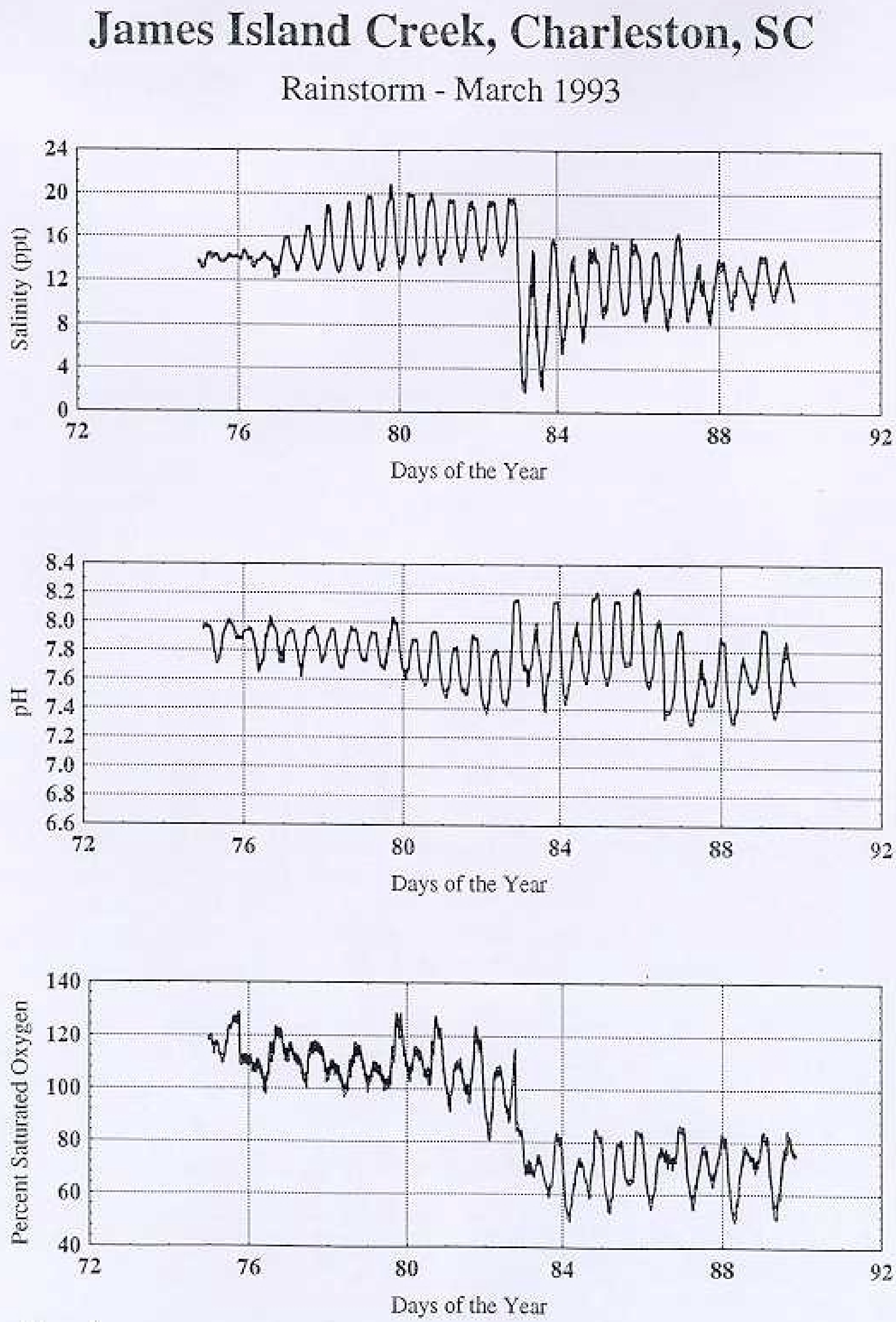

James Island Creek, Charleston, SC
Rainstorm - March 1993
Salinity (ppt)
Days of the Year
pH
Days of the Year
Percent Saturated Oxygen
Days of the Year

Figure 9.

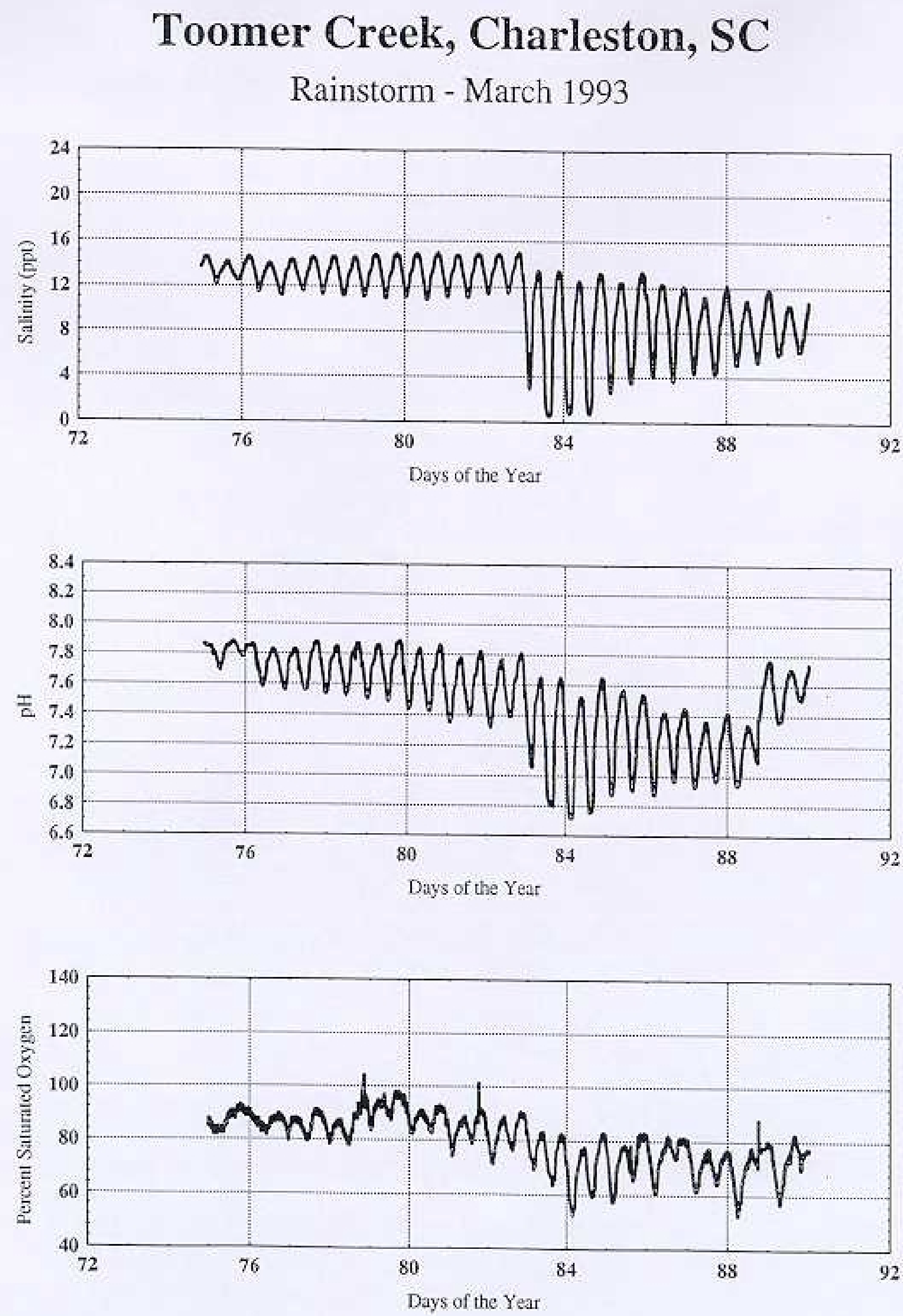


Figure 10.

The dynamics of the storm are more easily visualized using spectral analysis (Fig. 11 to 16). This analysis shows that each site displays a strong periodicity at 12 an 24 hours (possibly tidal and solar cycles). However, the ratio of the 12 to 24 hour peaks change post-rain at James Island Creek (approx. 3/4 to 1/3) and remains relatively constant at Toomer Creek (approx. 1/2). Examination of the power spectrum at wavelengths below 12 hours reveals that Toomer Creek displayed a stronger spectral density (sharper signal) at 6 hours in salinity, pH, and oxygen.

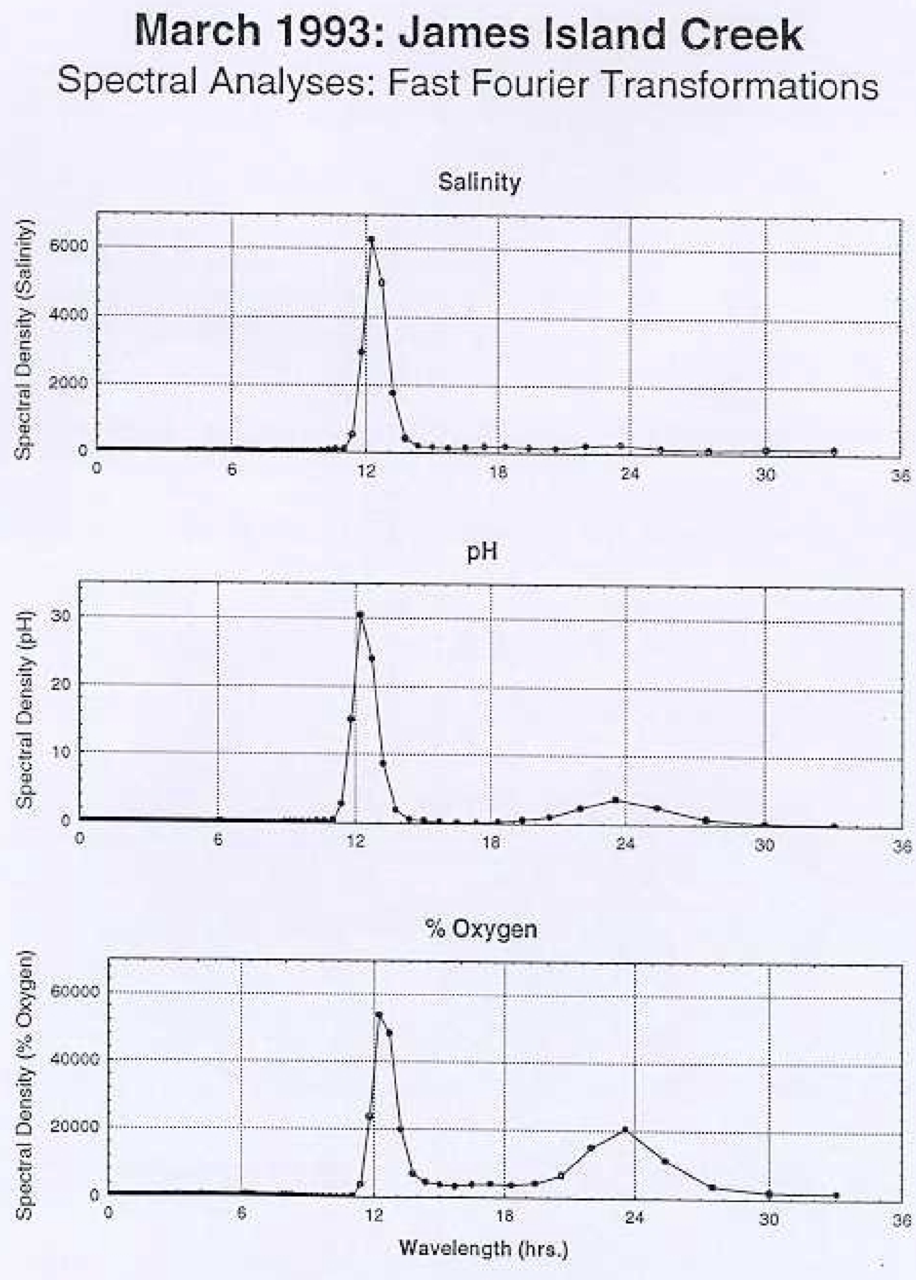

March 1993: James Island Creek
Spectral Analyses: Fast Fourier Transformations
Salinity
Spectral Density (Salinity)
0
2000
4000
6000
0
6
12
18
24
30
36
pH
Spectral Density (pH)
0
10
20
30
% Oxygen
Spectral Density (% Oxygen)
0
20000
40000
60000
Wavelength (hrs.)

Figure 11.

March pre-Rain 1993: James Island Creek

Spectral Analyses: Fast Fourier Transformations

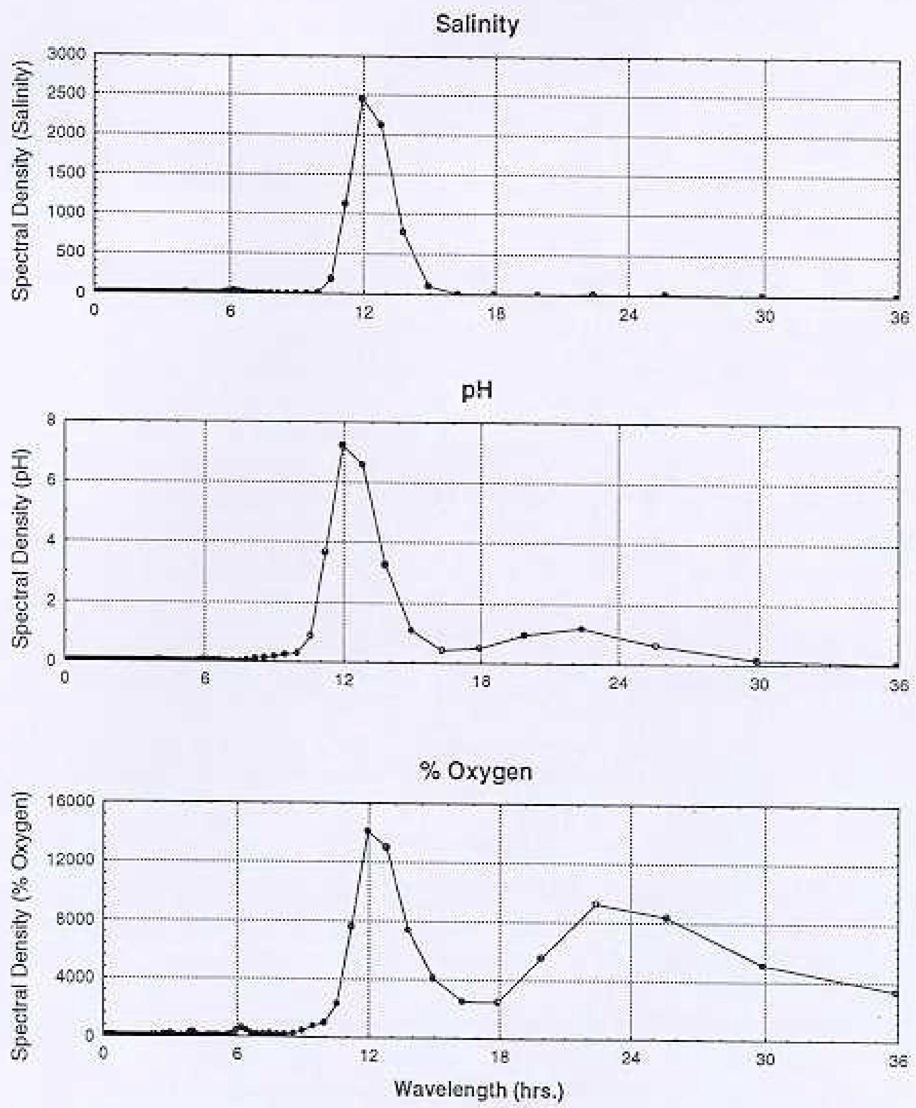


Figure 12.

March post-Rain 1993: James Island Creek

Spectral Analyses: Fast Fourier Transformations

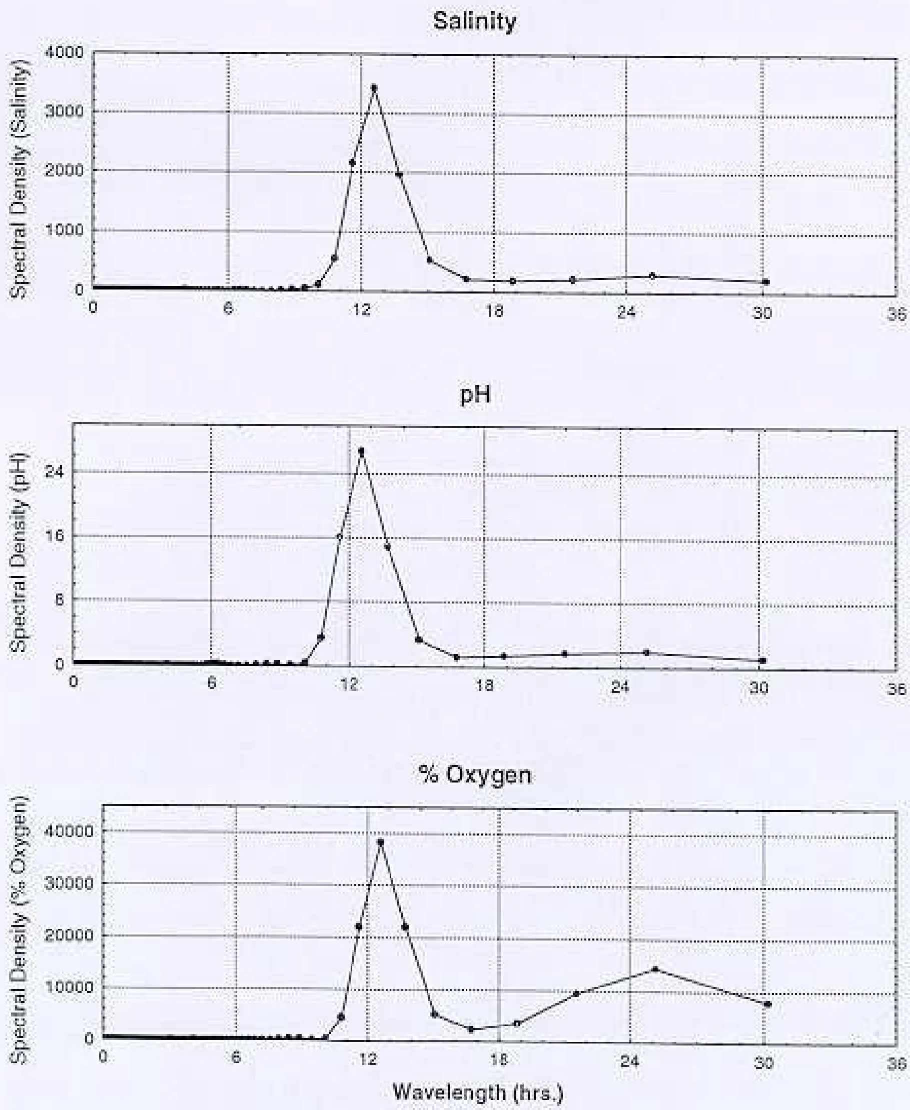


Figure 13.

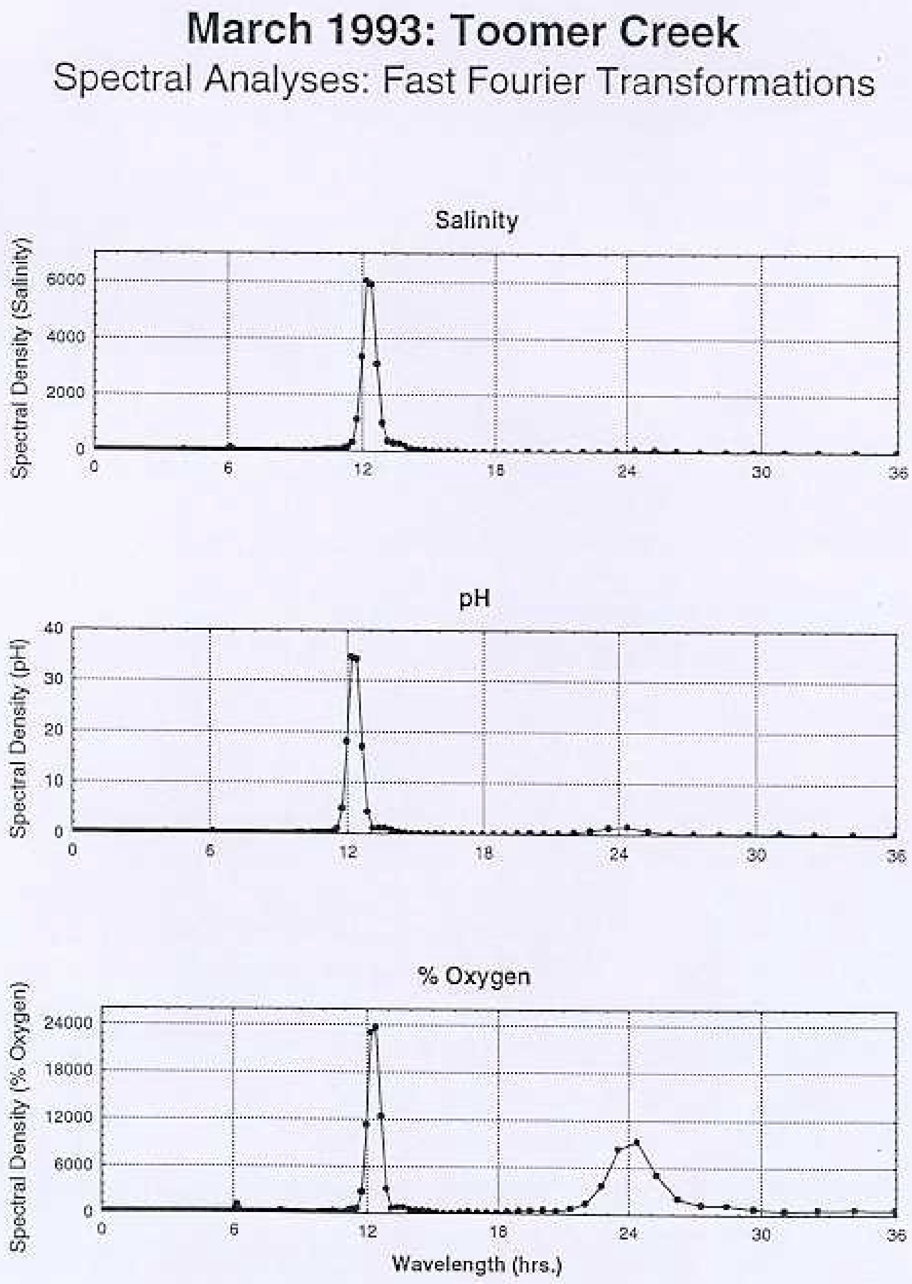

March 1993: Toomer Creek
Spectral Analyses: Fast Fourier Transformations
Salinity
Spectral Density (Salinity)
6000
4000
2000
0
0
6
12
18
24
30
36
pH
Spectral Density (pH)
40
30
20
10
0
0
6
12
18
24
30
36
% Oxygen
Spectral Density (% Oxygen)
24000
18000
12000
6000
0
0
6
12
18
24
30
36
Wavelength (hrs.)

Figure 14.

March pre-Rain 1993: Toomer Creek

Spectral Analyses: Fast Fourier Transformations

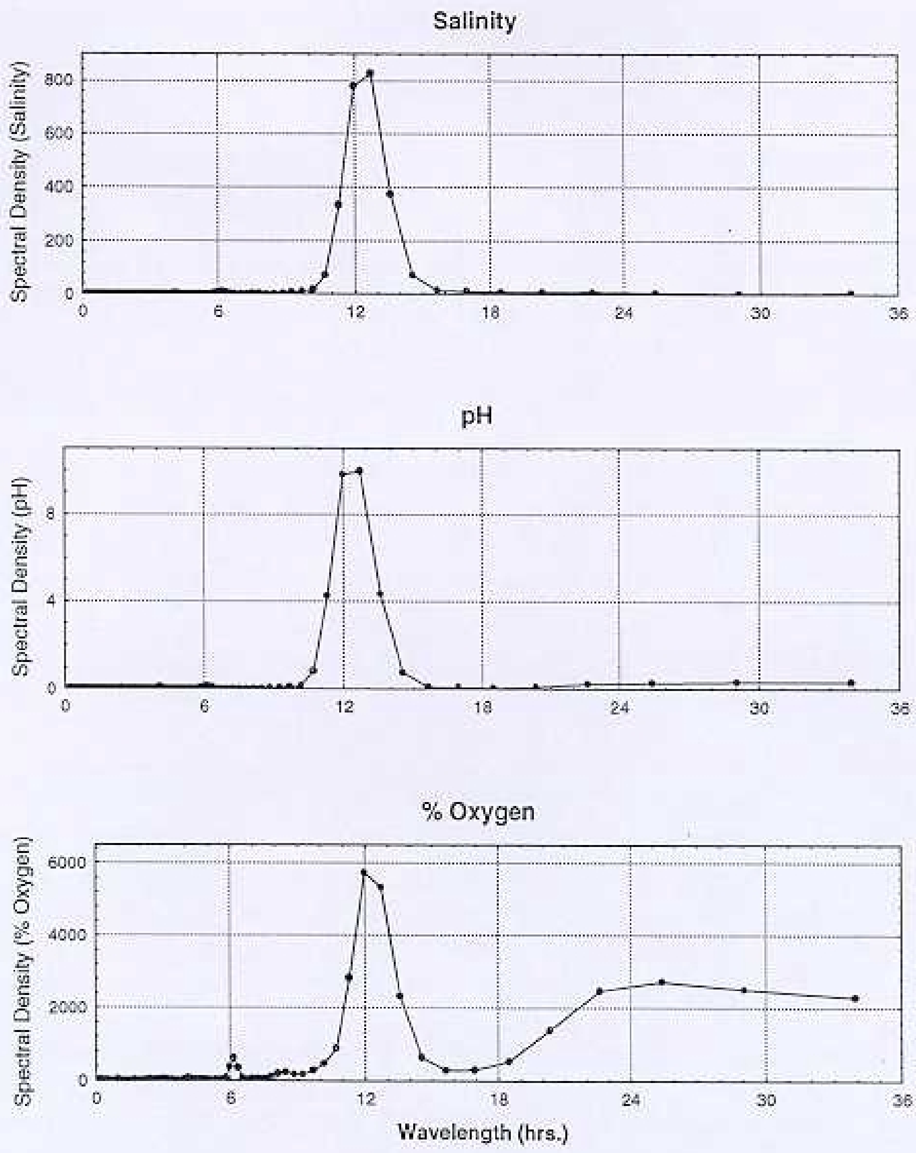


Figure 15.

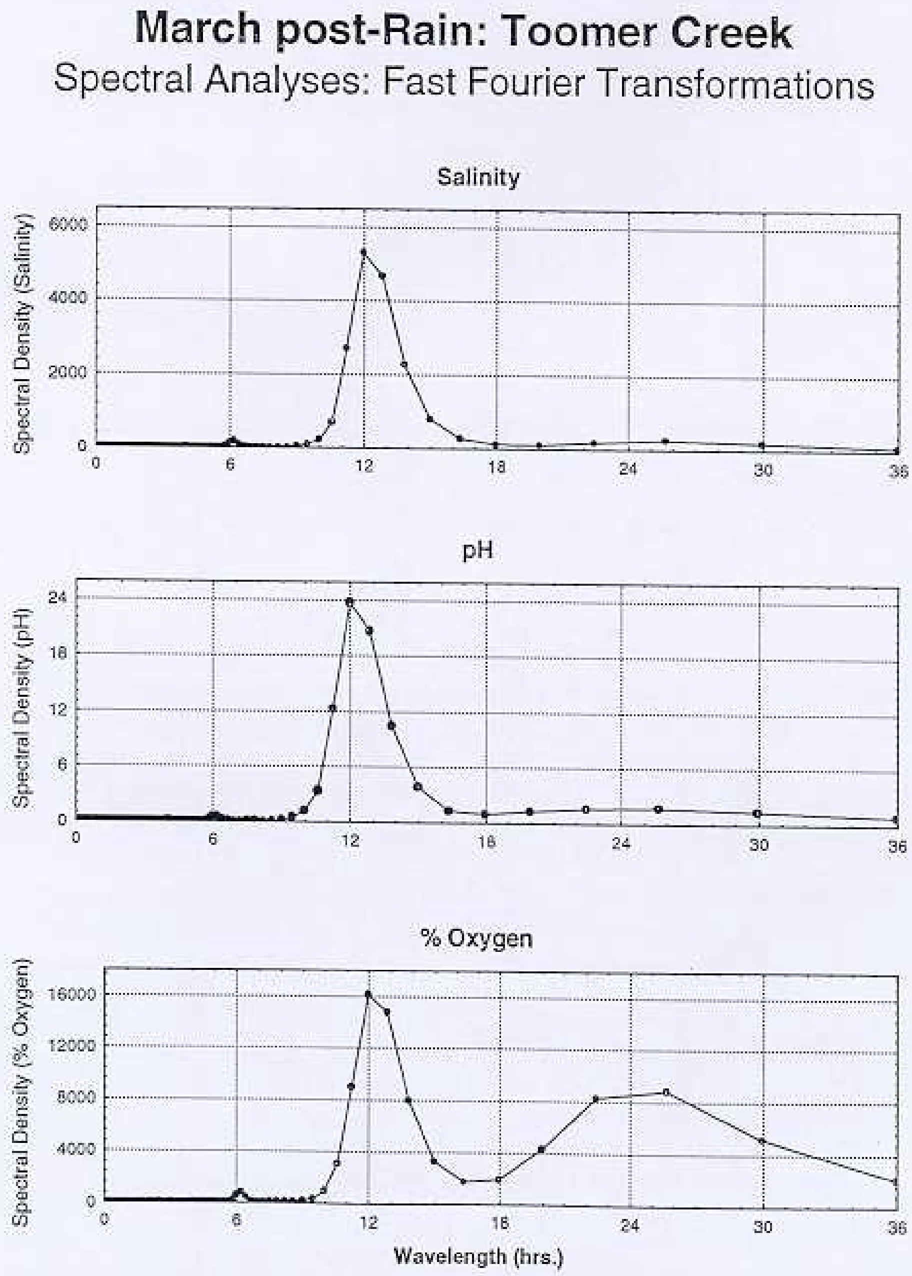


Figure 16.

Tropical Storm Jerry (James Island Creek).

The passage of Tropical Storm Jerry in 1995 after a relatively long period of drought afforded another glimpse into the dynamics of these estuarine creeks (Fig. 17). The prolonged drought before Tropical Storm Jerry's passage had the effect of dampening the variation in salinity (approx. 3 ppt range), presumably due to a lack of freshwater input during low tidal stages. The relationship between pH and salinity, and oxygen and salinity suggests that while oxygen and pH show a high degree of correlation in either drought or wet conditions, drought conditions seem to "collapse" the conservative aspect of the relationship with salinity (Fig. 18 and 19). As speculation, the input of groundwater may dilute the creek waters biomass on each tidal cycle, thus reducing the per unit respiration rate. During droughts freshwater input all but ceases and the relationship between respiration and salinity diminishes. Two days after the first rain, the oxygen content dropped by approximately 20% and stayed below pre-storm values for at least five or six days. Another rainstorm occured around day 243 which caused a further alteration in the pH and oxygen content signals.

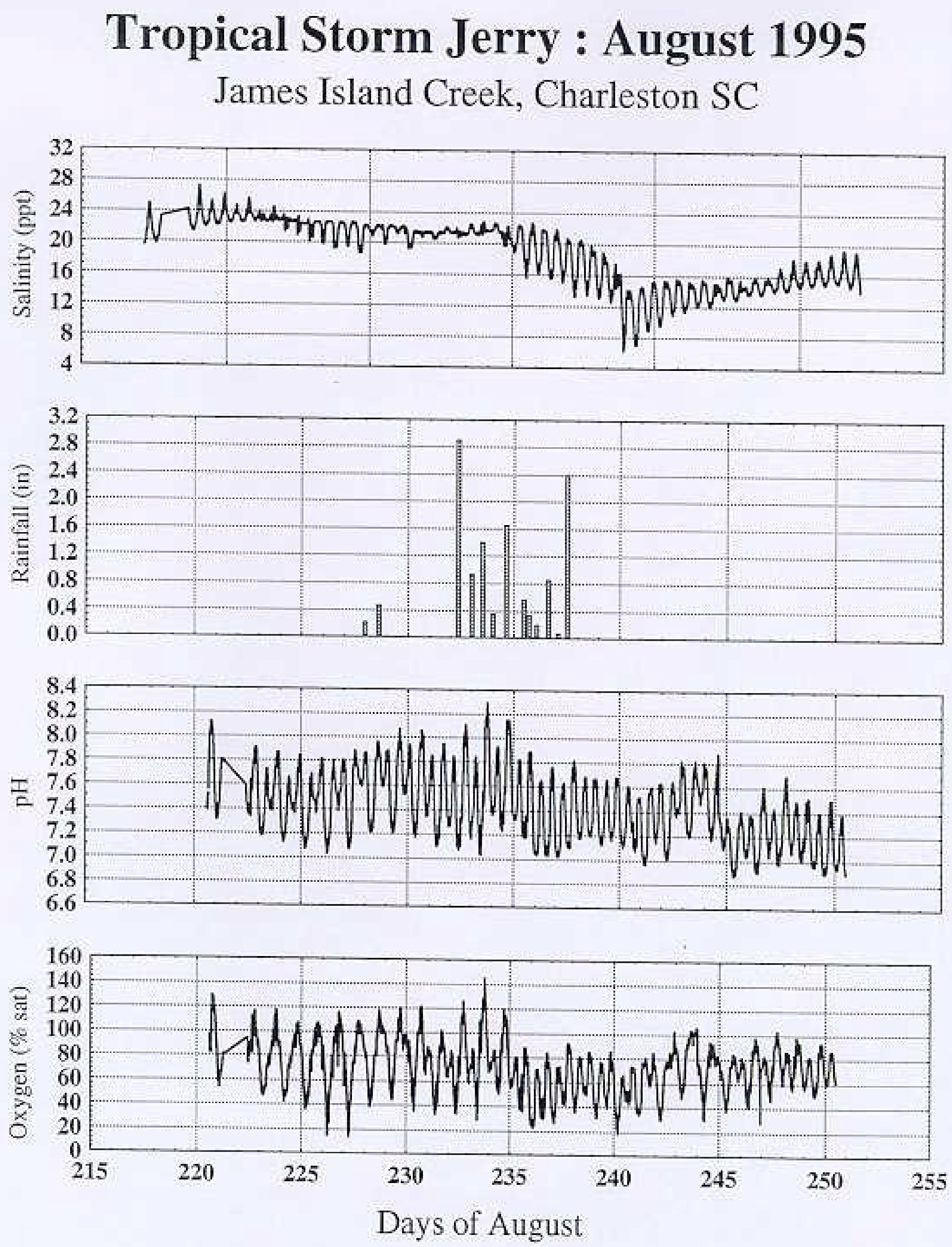

Tropical Storm Jerry : August 1995
James Island Creek, Charleston SC
Salinity (ppt)
32
28
24
20
16
12
8
4
Rainfall (in)
3.2
2.8
2.4
2.0
1.6
1.2
0.8
0.4
0.0
pH
8.4
8.2
8.0
7.8
7.6
7.4
7.2
7.0
6.8
6.6
Oxygen (% sat)
160
140
120
100
80
60
40
20
0
215
220
225
230
235
240
245
250
255
Days of August

Figure 17.

Tropical Storm Jerry : pre-Storm/dry

James Island Creek, Charleston SC

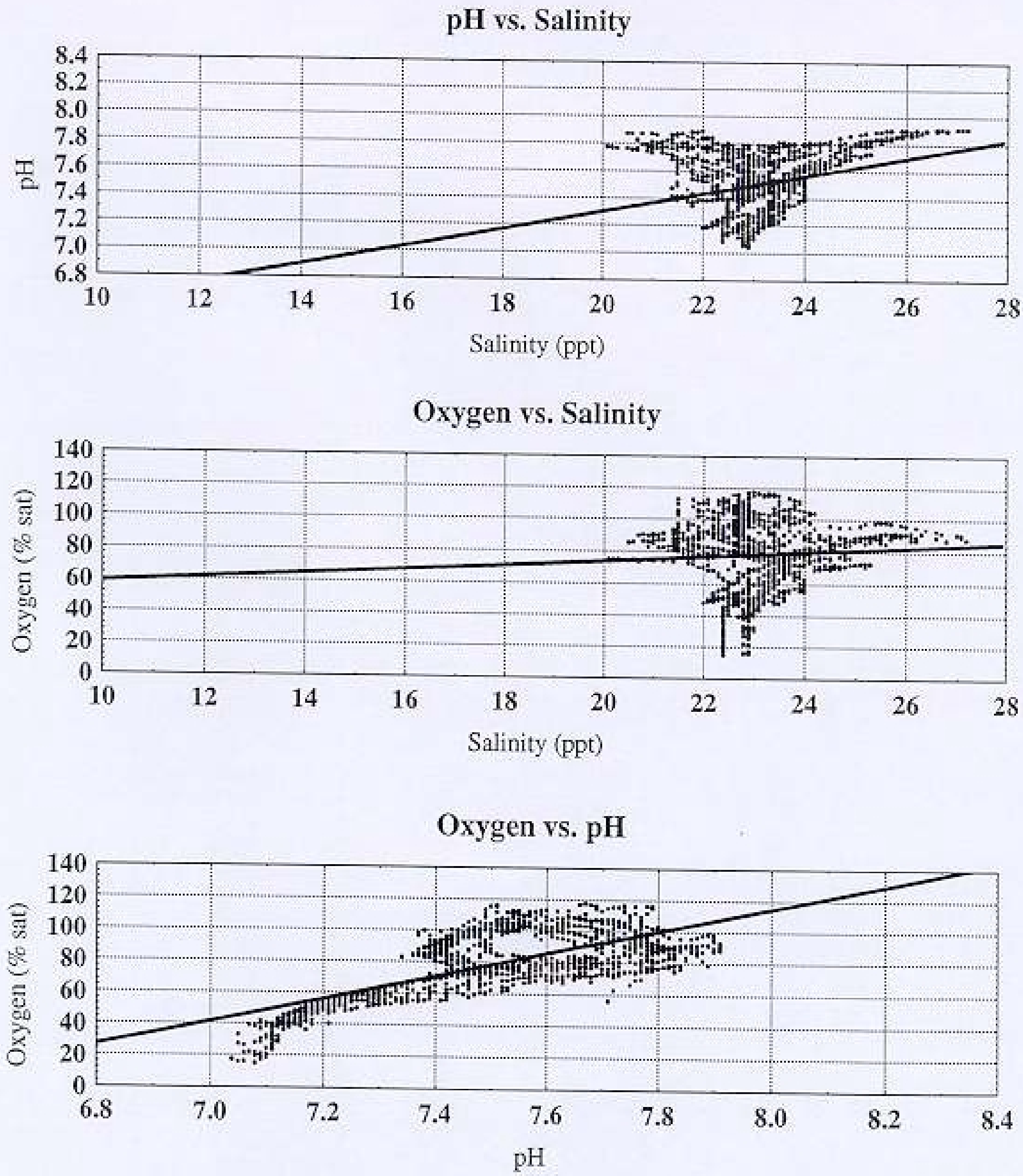


Figure 18.

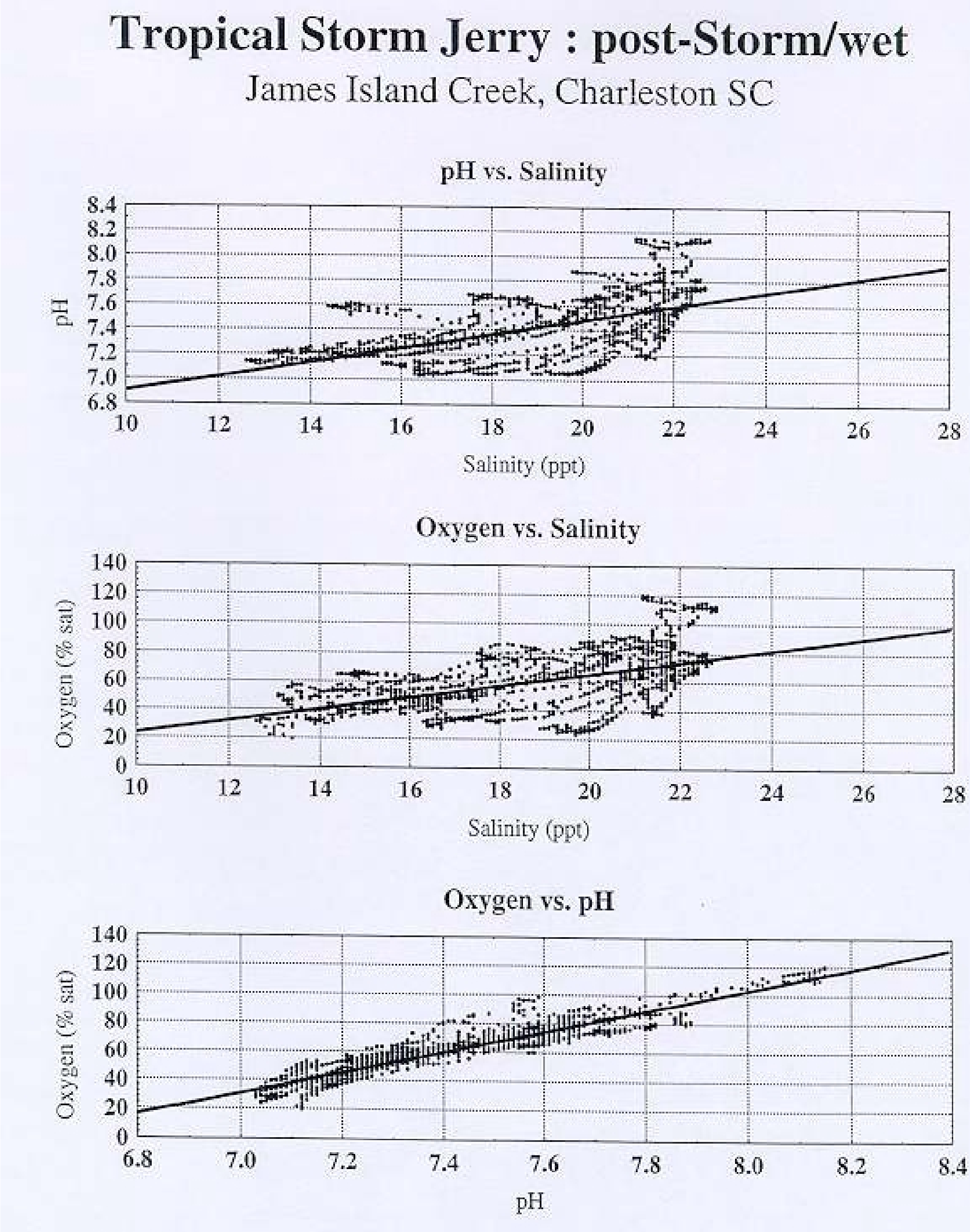


Figure 19.

Spectral analysis of the pre-storm data (Fig. 20 and 21) shows revealed a single broad peak in wavelength for salinity, a double peak in spectral density at

12 and 20 hours for pH, and a single peak centered at 24 hours for dissolved oxygen. Under drought conditions it appears that the dominant forcing function occurs with a 20 to 24 hour periodicity, perhaps the solar cycle.

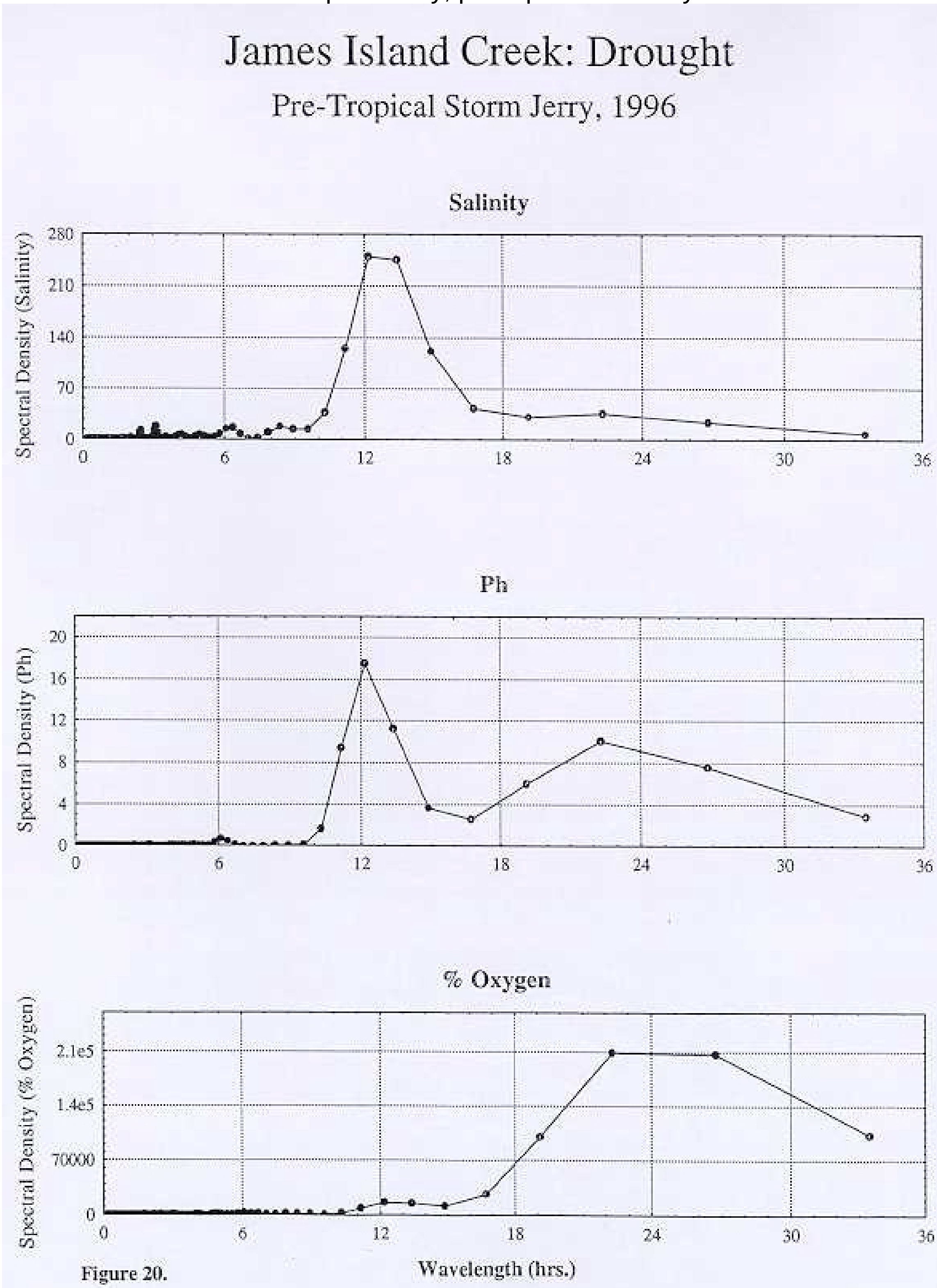


Figure 20.

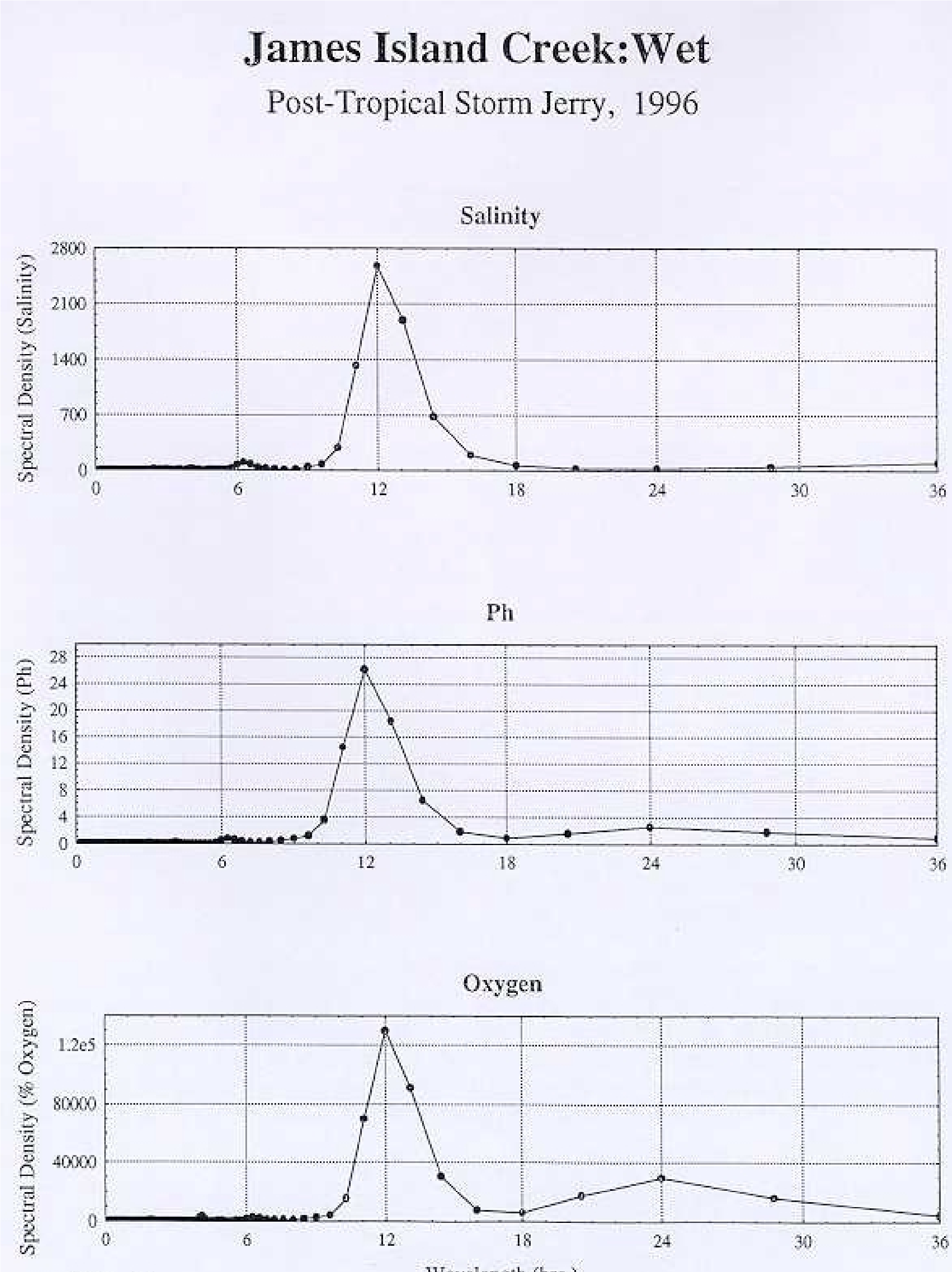


Figure 21.

Two days after the rains began (day 233) , a strong tidal signal reappeared in the salinity recording and pH and oxygen values dropped.

Spectral analysis indicated that salinity, pH and oxygen spectral densities shifted towards periodicity centered on a 12 hour wavelength. Thus, before the storm, creek metabolism displayed a dominant spectral density at 24 hours, which quickly reverted to the more commonly seen 12 hour, tidally linked signal. The input of storm water resulted in a lowering of estuarine oxygen concentration and apparently caused the creek to shift its “metabolic clock”, perhaps revealing a previously unknown linkage between weather and the patterns of variability of estuarine creeks.

Nutrients

Discrete nutrient sampling carried out at James Island Creek and Toomer Creek at hourly intervals during tidal cycles showed the data were highly variable. Nitrate ranged from .02 to .14 $mg \cdot l^{-1}$, nitrite .001 to .102 $mg \cdot l^{-1}$, phosphate .07 to 3.16 $mg \cdot l^{-1}$, and silicate .87 to 4.43 $mg \cdot l^{-1}$ (Appendix 2.). While there is no significant correlation between nutrients and salinity, the range of a variable increases with salinity, suggesting that the mainstream waters of Charleston Harbor, and the Wando River may be sources of nutrients for these estuarine creeks (Fig. 22.). An examination of the data with respect to tidal height suggests that nutrient levels appear higher at low tide on some occasions. While these observations reinforce the dual gradient concept that both mainstem and source waters contribute to the distribution of materials in estuaries, more data are needed to address this question (Appendix 3.).

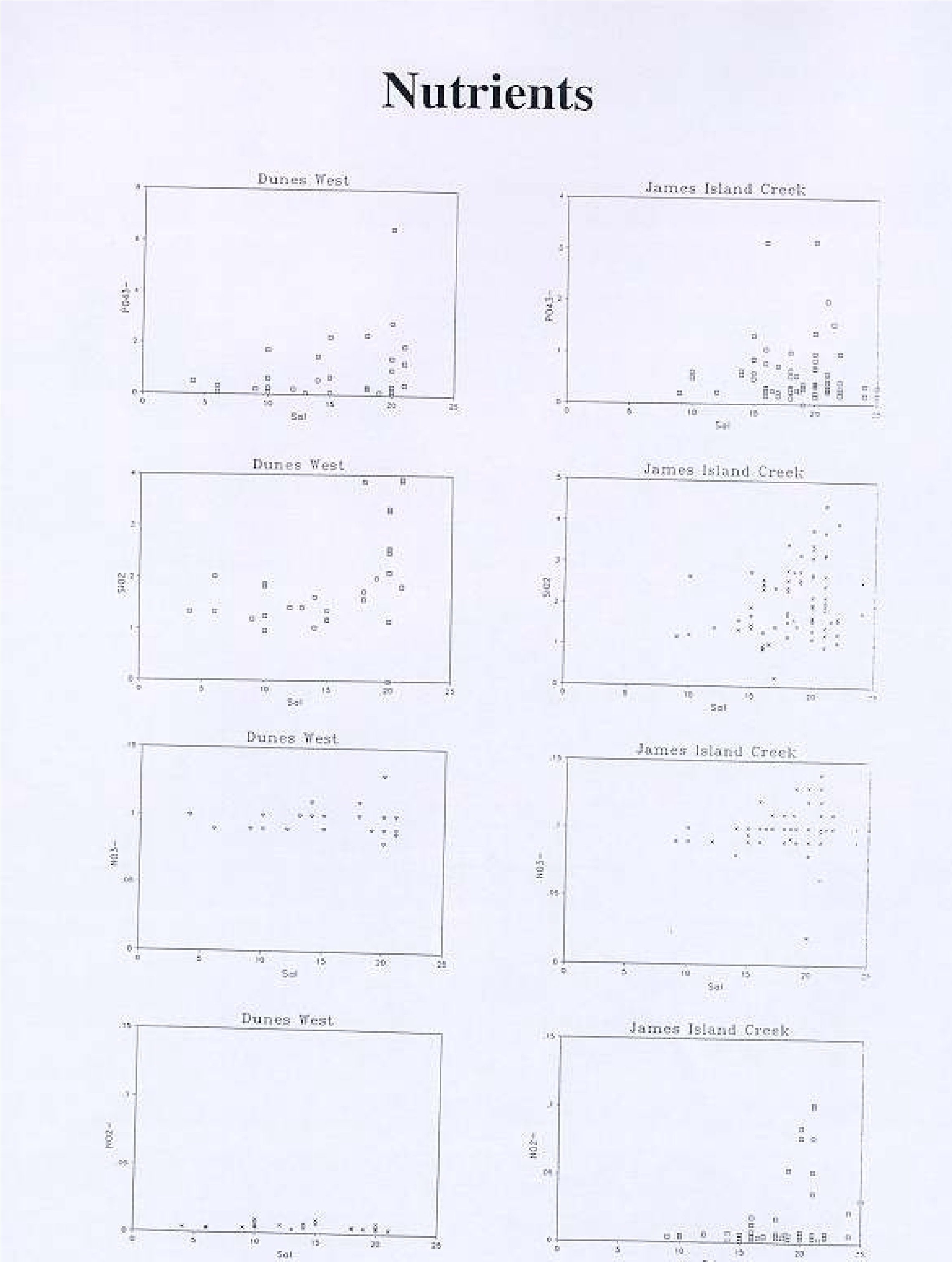


Figure 22.

During one sampling period (19 July) at Toomer Creek, a large thunderstorm dropped approximately one inch of rain in an hour period. Nutrient levels spiked a few hours later perhaps due to leaching or elevated nutrients in the rainwater itself. The rapidity at which the levels spiked illustrates the speed that water moves through the sandy soils of a forested ecosystem and into the estuarine waters.

Biological Oxygen Demand

Summer 1994 was marked by one of the wettest, and most continuously wet, summers on record. We had hoped to carry out a series of pre/post rain experimental incubations, but rainfall patterns were such that it almost never dried out. Under these abnormal conditions, a single series of experimental incubations on water column respiration rates before and after rain events were completed. The data, although variable, demonstrated that the water column respiration rates increase significantly after a rain event (Fig. 23). However, there appears to be threshold below which the rainfall does not trigger a short term oxygen depletion event and higher rainfall amounts apparently washout the system through “overflooding”.

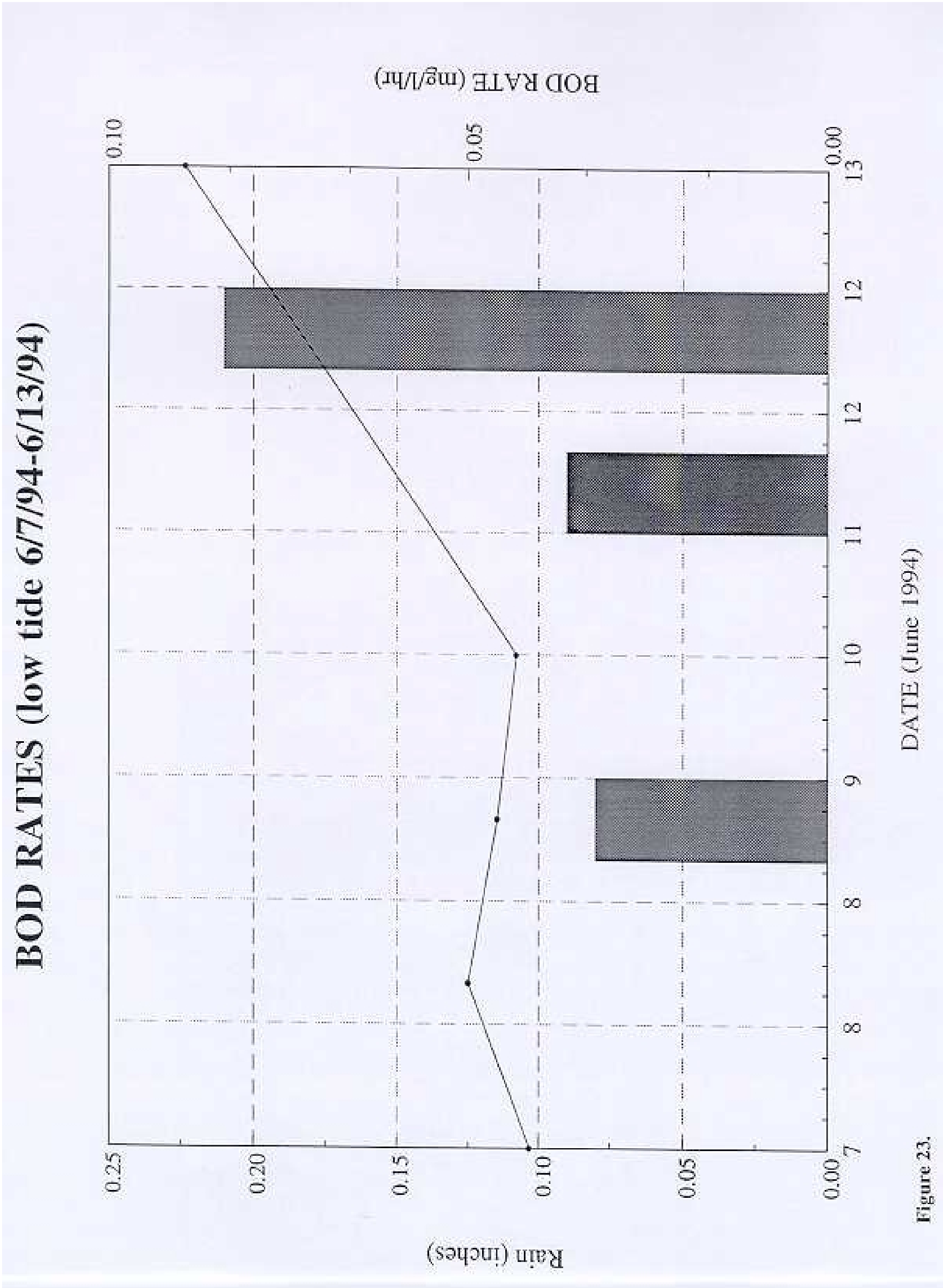

BOD RATES (low tide 6/7/94-6/13/94)
BOD RATE (mg/l/hr)
0.10
0.05
0.00
Rain (inches)
0.25
0.20
0.15
0.10
0.05
0.00
7
8
8
9
10
11
12
12
13
DATE (June 1994)

Figure 23.

Discussion

As the tide floods and ebbs in estuarine creeks, friction with the sides and bottom of the estuary causes tidal waves and currents which mix the water column (Pelegri , 1988; Blumberg and Goodrich, 1990; Sherwood et al., 1990; Simpson et al., 1990; Uncles and Stephens, 1990; Uncles and Stephens, l990b). These creeks are relatively narrow and while their maximum depths may approach 10 meters in a few areas, they are relatively shallow in relations to the fluctuation in tidal height which can be in excess of 1.8 meters. Bridges, boats and anything in the water can create turbulence and mix the water column (Kuo and Neilson, 1987; Schroeder et al., 1990). Thus, the overturn of the tides probably mixes the estuarine creeks from top-to-bottom during each tidal cycle well enough so that a measurement made at a single point is representative of the creek in general. With this in mind , the general descriptive summary statistics for the entire sampling periods do not reveal any dramatic differences between the two creeks, even though one has a highly urbanized watershed and the other was principally forested.

However, the analysis of the high frequency data suggests that these two creeks differ in their response to periods of intense rainfall; perturbations caused by rainfall seems to have a larger impact on creeks with urbanized watersheds. James Island Creek with its urbanized watershed has a weaker high frequency periodic signal. This may result from the urbanized watershed being more channeled; with increased sheet runoff, which tends to reflect the periodicity of the rainfall while partially disrupting or masking the tidal signal. Toomer Creek, on the other hand, reacts to a rainstorm as though it were a string which, if suddenly plucked vibrates back to its central frequency; the rainfall is intercepted by the land and released into the estuary through groundwater seepage.

Runoff from a storm enters the urbanized estuary quickly from roadways, lawns, and storm drains generating a signal with increased variance and range. Rainfall events in the less developed watershed appear to be "ecologically damped" as the range and amplitude of variation after a rainfall is considerably less. Salinity changes are not as sharp, and pH and O_2 are less variant after rainstorms of equivalent magnitude. One explanation for these differences appears to be linked to the alterations that occur in the hydrodynamics of urbanized watersheds. The early stages of urbanization tend to dramatically increase rates of soil erosion, but once houses are built and the disturbance ceases, urban lands may have very low rates of erosion (Goudie, 1990). Later, because urbanization increases the surface of impermeable substrates (roads, roofs, driveways) the runoff from flood rains occurs sooner and may be greater than in forested systems. Runoff tends to become more channeled with the construction of roads and drainage systems which results in peak discharges occurring sooner and at higher rates along a more direct pathway into the estuary (Hopkinson and Vallino, 1995).

In forested watersheds, the canopy intercepts rainfall which reduces the erosive effect of rain. Additionally, humus on the forest floor increases the permeability of the soil. Forest soils tend to be less compact than urban soils because roots and soil fauna form microchannels for water to infiltrate into the ground. These same features tend to conserve sediment loss, which can be 10 to 100 times higher in small urbanizing areas and developed or industrialized areas (Correll et al., 1992; Hopkinson and Vallino, 1995).

This study produced a detailed record of variability of two estuarine creeks, one forested, the other urbanized. The two differed little in their annual variability, but there were characteristic changes resulting from storms that suggest range and urban development alters the patterns of natural variability during storm events making conditions more unpredictable (higher variability) and, at the same time, increasing the biological oxygen demand through increased water column respiration rates resulting from increased microbial activity. James Island Creek showed a deeper and more immediate drop in oxygen concentration as a result of rainstorms. Such a drop may be caused by increases in water column respiration, demonstrated experimentally for a different storm. The concomitant changes in pH and O_2 are hypothesized to result from a loss or organic carbon which, once imported into the estuary, cause an increase in biological oxygen demand. While a macroscale event such as Hurricane Hugo, can have dramatic effects on oxygen content, urbanization, and development in general, may apply a chronic stress over a period of years (Howarth, et al, 1991). Such chronic stress may alter the natural selective forces on the creek community which may effect primary production, community structure and/or biodiversity. While it is clear that much more work needs to be done to clarify the dynamics of short term oxygen depletion (STODE effect), the perturbations caused by rainfall seem to have a larger impact on urbanized watersheds than in the less developed ones. With this in mind, thought needs to be given towards denying rainwater unhindered access to estuarine creeks. The urban lawn could be allowed to revert to urban forest landscapes, buffer strips could be implemented to trap the sediments and organic carbon transported by sheet flow, Stormwater drainage systems could be designed for new and existing developments that better mimic the path of runoff in natural systems.

Acknowledgments

Numerous College of Charleston students were employed during this period. Special thanks are due to those who worked in the field and laboratory, on both wet and dry aspects of this research project: graduate students Shirley Conner, Allison King, Michael Taylor, and undergraduate assistants Heidi Baker, Jerry Chapman, Eric Marriot, Paul Martin, Dan Pescio, Dan Russ, and Laura Schrum. George Nelson and Michael Brill assisted in the preparation of imagery and figures.

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List of Figures.

List of Figures (cont).

Appendix 1. Variation in water quality by month:
James Island Creek and Toomer Creek.

*Available upon request from SC DHEC-OCRM, 1362 McMillan Avenue, Charleston, SC 29405

Appendix 2. Dissolved nutrients for James Island Creek (JIC).

	DATE	TIME	NO3-	NO2-	PO43-	SiO2	SAL	TIDE	REMARKS
JIC	6/4/93	730	0.10	0.007	0.25	1.28	21	4.7	
		835	0.11	0.006	0.31	1.62	22	5.2	
		935	0.10	0.004	0.28	1.64	19	5.0	
		1035	0.10	0.003	1.56	1.62	22	4.1	
		1135	0.10	0.006	0.44	2.48	21	2.7	
		1240	0.09	0.005	0.55	2.82	19	1.1	
		1340	0.10	0.004	0.30	3.25	21	-0.1	
		1445	0.09	0.005	0.54	3.48	18	-0.5	
		1545	0.10	0.004	0.34	3.76	21	0.1	
		1710	0.10	0.005	0.99	4.00	22	2.0	
		1750	0.11	0.007	0.26	1.48	19	3.1	
		1905	0.11	0.005	0.30	1.23	18	4.9	
		2005	0.11	0.005	0.16	1.46	17	6.1	
		mean	0.10	0.01	0.48	2.32	20	2.9	
		stdev	0.01	0.00	0.39	1.02	2	2.3	
JIC	6/14	300	0.10	0.003	0.33	0.92	16	4.2	
		400	0.10	0.004	0.26	1.04	17	4.5	
		500	0.10	0.005	0.24	0.22	17	4.4	
		600	0.10	0.004	0.26	2.44	18	3.8	
		700	0.10	0.003	0.69	2.70	20	2.9	
		800	0.08	0.003	0.37	3.16	20	1.9	
		900	0.09	0.003	0.39	2.55	19	1.1	
		1000	0.08	0.005	0.37	2.76	20	0.6	
		1100	0.09	0.004	0.28	1.45	21	0.7	
		1200	0.12	0.004	0.31	2.38	16	1.4	
		1300	0.10	0.005	0.74	2.42	17	2.4	
		1400	0.09	0.005	0.66	2.35	18	3.5	
		1500	0.10	0.005	0.16	2.49	16	4.4	
		mean	0.10	0.004	0.39	2.07	18	2.7	
		stdev	0.01	0.00	0.19	0.87	2	1.5	

Appendix 2. (cont.). Dissolved nutrients for James Island Creek (JIC).

	DATE	TIME	NO3-	NO2-	PO43-	SiO2	SAL	TIDE	REMARKS
JIC	6/15	400	0.09	0.006	3.14	0.93	16	4.2	
		500	0.02	0.008	1.38	2.01	20	4.5	
		600	0.10	0.007	0.13	2.60	18	4.3	
		700	0.10	0.006	0.71	1.38	20	3.6	
		800	0.10	0.004	3.16	3.36	20	2.7	
		900	0.09	0.004	1.38	3.46	20	1.7	
		1000	0.09	0.005	1.01	2.84	18	0.9	
		1100	0.10	0.006	0.87	2.79	15	0.4	
		1200	0.10	0.006	0.49	1.42	15	0.6	
		1300	0.10	0.008	0.79	1.00	16	1.5	
		1400	0.10	0.006	0.00	2.82	19	2.7	
		1500	0.10	0.006	0.21	1.99	20	3.8	
		1600	0.10	0.005	0.15	1.70	20	4.7	
		mean	0.09	0.01	1.03	2.18	18	2.7	
		stdev	0.02	0.00	1.04	0.86	2	1.6	
JIC	6/19	810	0.10	0.005	0.26	1.09	22	4.7	
		915	0.10	0.004	0.18	1.31	22	4.5	
		1015	0.10	0.008	0.44	1.69	22	3.7	
		1115	0.09	0.004	0.50	2.71	21	2.6	
		1215	0.09	0.004	0.51	2.68	10	1.3	
		1315	0.09	0.005	0.40	2.19	20	0.3	
		1415	0.09	0.005	0.41	3.82	20	-0.2	
		1515	0.06	0.003	0.33	4.43	21	0.2	
		1615	0.10	0.004	0.34	3.22	19	1.4	
		1715	0.09	0.003	0.60	1.94	15	2.9	
		1815	0.10	0.004	1.33	1.74	15	4.4	
		1915	0.10	0.001	0.86	1.51	15	5.5	
		2015	0.08	0.002	0.65	1.38	14	6.2	
		mean	0.09	0.00	0.52	2.28	16	4.1	
		stdev	0.01	0.00	0.30	1.03	2	2.0	

Appendix 2. (cont.). Dissolved nutrients for James Island Creek (JIC).

	DATE	TIME	NO3-	NO2-	PO43-	SiO2	SAL	TIDE	REMARKS
JIC	8/5	915	0.10	0.031	0.33	2.00	25	4.7	
		1000	0.11	0.032	0.185	1.04	25	5.1	
		1100	0.14	0.102	0.39	2.07	21	5.3	
		1200	0.12	0.053	0.25	0.96	21	4.9	
		1310	0.10	0.008	0.36	1.60	20	3.8	
		mean	0.11	0.05	0.30	1.53	22	4.8	
		stdev	0.02	0.04	0.08	0.52	2	0.6	
JIC	8/11	810	0.11	0.018	0.34	1.83	18	0.9	
		900	0.10	0.014	1.07	2.61	16	0.8	
		1000	0.10	0.019	0.26	1.32	16	1.2	
		1100	0.11	0.037	0.33	3.19	21	2.1	
		1200	0.13	0.054	0.30	2.62	19	3.2	
		1410	0.13	0.101	2.00	1.98	21	5.0	
		mean	0.11	0.04	0.72	2.26	19	2.5	
		stdev	0.01	0.03	0.70	0.67	3	1.7	

Appendix 2. (cont.). Dissolved nutrient values for Toomer Creek (TC)

SITE	DATE	TIME	NO3-	NO2-	PO43-	SiO2	SAL	TIDE	REMARKS
TC	7/19	930	0.10	0.005	0.20	2.57	20	6.4	
		1030	0.09	0.003	0.20	2.54	20	6.3	
		1130	0.09	0.003	0.05	N/A	20	5.3	
		1230	0.08	0.004	2.82	3.31	20	3.6	
		1330	0.09	0.012	1.25	3.89	21	1.6	1530-1630
		1430	0.09	0.003	0.40	3.92	21	0.0	(1" rain)
		1530	0.13	0.004	1.43	2.57	20	-0.6	
		1630	0.10	0.004	2.35	3.87	18	0.0	
		1830	0.10	0.008	6.50	3.35	20	3.4	
		1930	0.10	0.003	1.91	1.85	21	5.2	
		2030	0.08	0.003	0.15	2.49	20	6.7	
		mean	0.10	0.00	1.57	2.76	20	3.0	
		stdev	0.01	0.00	1.90	1.15	1	3.2	
TC	8/4	900	0.11	0.004	1.50	1.03	14	5.0	
		1000	0.10	0.007	0.69	1.37	15	5.9	
		1100	0.09	0.004	0.11	2.00	19	6.5	
		1200	0.10	0.003	0.07	1.42	13	6.4	sprinkling
		1300	0.10	0.004	0.50	1.34	4	5.4	since 1400
		1400	0.09	0.004	0.10	1.33	6	3.8	hard rain fo
		1600	0.09	0.005	0.34	2.11	20	0.7	35 minutes
		1700	0.10	0.010	0.27	1.84	10	0.4	
		1900	0.10	0.007	0.10	0.97	10	2.3	
		mean	0.10	0.01	0.41	1.49	10	2.5	
		stdev	0.01	0.00	0.46	0.40	6	2.1	
TC	8/5	930	0.10	0.005	0.98	1.17	20	4.9	
		1030	0.10	0.007	0.57	1.62	14	5.9	
		1130	0.09	0.006	0.23	1.42	12	6.4	
		1230	0.09	0.004	0.21	1.20	9	6.4	
		1330	0.10	0.005	0.63	1.26	10	5.6	
		1430	0.10	0.005	0.24	1.75	18	4.0	
		1530	0.11	0.004	0.32	1.59	18	2.4	
		mean	0.10	0.01	0.45	1.43	13	5.0	
		stdev	0.01	0.00	0.29	0.23	4	1.8	

Appendix 2. (cont.). Dissolved nutrient values for Toomer Creek (TC)

	DATE	TIME	NO3-	NO2-	PO43-	SiO2	SAL	TIDE	REMARKS
TC	8/11	900	0.09	0.003	0.33	2.03	6	1.1	
		1100	0.09	0.004	1.75	1.88	10	1.7	
		1300	0.09	0.010	0.10	1.18	15	4.1	
		1400	0.10	0.007	2.27	1.20	15	5.2	
		mean	0.09	0.01	1.11	1.57	12	3.0	
		stdev	0.00	0.00	1.06	0.45	4	1.9	

Appendix 3. Dissolved nutrient content in relation to tidal height:
James Island Creek (JIC) and Toomer Creek (TC).

*Available upon request from SC DHEC-OCRM, 1362 McMillan Avenue, Charleston, SC 29405